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Optimal harvesting of *Tectona grandis* plantation stands in Costa Rica

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Tiivistelmä/Referat–Abstract

This thesis studies the economically optimal timing of thinnings and final harvest on Costa Rican *Tectona grandis* plantations. Consequently this thesis studies the profitability of the plantations and makes a comparison to previous studies. Optimization is based on programming with AMPL with Knitro optimizing software. The objective function used is the Faustmann formula. Different rates of interest are used. The ecological functions used for the modeling were obtained from previous studies by Pérez and Kanninen (2005a). The economic data such as planting and thinning costs and log prices were obtained from a *T. grandis* plantation specialist.

The results of the study show that the optimal harvesting regime in *T. grandis* plantations differs from what is suggested in literature. The main findings are that the optimal rotation length is shorter and both timing and intensity of the thinnings vary depending on the rate of interest used. In addition the maximized bare land values under optimal management regimes are notably higher than bare land values under previously suggested management regimes. The management regime is highly sensitive to the rate of interest used. The management regime is less sensitive to the changes in price than expected. This thesis suggests that the initial density of 816 trees ha^{-1} results into higher bare land values than 1111 trees ha^{-1}. However, the difference is minor and possible increase in silvicultural costs is not considered. In addition a simple test is carried out to see the possible effects on heartwood proportion growth to the optimal management regime. The shortcomings and possibilities to improve the model are discussed. It is noted that the price data for *T. grandis* is not coherent, and that the ecological model could be improved in order to increase its accuracy.

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Optimization, Tectona grandis, single-tree model, plantation, sensitivity analysis, profitability, bare land value

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Tiivistelmä/Referat – Abstract

Tämä pro gradu -tutkielma tutkii *Tectona grandis* -puuviljelmien optimaalista harvennusta ja päätehakkuuta Costa Ricassa. Tutkielma analysoi *Tectona grandis* -puuviljelmien kannattavuutta edellä mainitun optimaalisen käsittelyn alaisena ja vertailee tuloksia aiempiin tutkimuksiin. Tutkimuksen optimointi perustuu AMPL ohjelmointiin, joka on ratkaistu käyttäen Knitro optimointisovellusta. Tutkimuksessa käytettävä tavoitefunktio on Faustmannin kaava, eli tavoitteena on paljaan maan arvon maksimoiminen. Optimoinnissa käytettiin eri korkokantoja. Ekologinen kasvumalli perustui Pérezin ja Kannisen aiempiin tutkimuksiin (2005a). Hinta- ja kustannustiedot saatiin *T. grandis* -puuviljelmien asiantuntijalta. Tutkimuksen tulokset osoittavat, että optimaalinen *T. grandis* -puuviljelmän käsittely on erilainen kuin kirjallisuudessa on aiemmin ehdotettu. Merkittävimmät havainnot ovat, että optimaalinen puuston kiertoaika on usein lyhyempi ja sekä harvennusten ajoitus että voimakkuus vaihtelevat käytetyn korkokannan mukaan. Lisäksi tutkimus osoittaa, että maksimoitu paljaan maan arvo on merkittävästi korkeampi käytettäessä optimoitua metsänkäsittelyä kuin käytettäessä aiemmin ehdotettuja metsänkäsittelyohjelmia. Tutkimuksessa havaittiin, että käytetyllä korkokannalla on huomattava vaikutus metsänkäsittelyyn. Puun hintojen vaikutus optimaaliseen käsittelyyn oli luultua pienempi. Tutkimus ehdottaa, että 816 puun istutustiheys hehtaarilla on hieman parempi kuin 1111 puun istutustiheys. Ero kahden eri alkutiheyden välillä paljaan maan arvossa ei ollut merkittävä ja väljempi istutustiheys voi johtaa kasvaviin kustannuksiin metsänhoitotoimenpiteissä, mitä ei huomioitu tulosten laskennassa. Lisäksi testattiin sydänpuun kasvun vaikutusta optimaaliseen käsittelyyn. Lopuksi analysoitiin tutkielmassa käytetyn mallin puutteita ja kuinka mallia olisi mahdollista parantaa. Todettiin, että hintatietoja on tarkennettava ja ekologista mallia olisi mahdollista parantaa lisäten sen tarkkuutta.

Avainsanat – Nyckelord – Keywords

Optimointi, yhden puulajin metsä, *Tectona grandis*, tiikki, puuviljelmä, herkkyysanalyysi, kannattavuus, paljaan maan arvo

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ABBREVIATIONS

AMPL	A Mathematical Programming Language
BLV	Bare Land Value
CF	Competition Factor
DBH	Diameter at Breast Height
FONAFIFO	Fondo Nacional de Financiamiento Forestal (The National Forestry Financing Fund)
IRR	Internal Rate of Return
ITTO	International Tropical Timber Organization
KNITRO	Nonlinear Interior point Trust Region Optimization (the “K” is silent)
MAI	Mean Annual Increment
NPV	Net Present Value
PPSA	Programa de Pago por Servicios Ambientales (Payment for Ecosystem Services)
tCO2e	Tonnes of CO2 equivalent
USD	United States Dollar

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1 INTRODUCTION

In recent decades there has been a growing interest towards *Tectona grandis* (L.f.) plantations. *Tectona grandis* is better known with its common name ‘teak’. *T. grandis* is considered as a highly valuable timber material in furniture production, shipbuilding industry and constructions (de Vriend 1998, p. 8). The primary target in *T. grandis* growing has been the productive use as timber instead of protective use, unlike with some other plantation tree species or plantations with mixed species. *T. grandis* plantations are seen as interesting investment targets due to its high value and fast growth. Even though *T. grandis* as a species has been long studied and major economic interest have been shown towards it, only few economic studies can be found related to it and even less attempts to optimize the plantation management regime in order to maximize the discounted net present value (see e.g. Jayaraman and Rugmini 2008). It may be argued for example that people are optimizing their daily life by choosing actions, which they think are benefiting them most. By introducing mathematics with the help of computer calculations a remarkably more accurate and faster optimization becomes possible within the limits determined by the accuracy of the model used. Our study aims to give such practical example of applying mathematical programming in order to optimize *T. grandis* plantation management regime when the objective is to maximize the bare land value.

Today the economic justification for *T. grandis* plantation management regime is based on internal rate of return (IRR) calculations, on net present value (NPV) calculations and on empirical observations of corresponding parallel plantations (Seppänen 2012). It seems that the plantation management regimes have been set from non-economic perspective, usually according to thinning tests and by seeing how those affect the competition and growth factors in the plantation, without taking into consideration the interest rates or the changes in prices.

Some international investors have been tricked into *T. grandis* investment schemes that have been nothing more than frauds and some have been let to believe that the expected profits are higher than they actually are (see e.g. Scholtens and Spierdijk 2007). Obviously such schemes create distrust around not only international investment opportunities in general, but additionally give bad reputation for *T. grandis* plantations as investments. In this thesis we aim to shed some light on the profitability of *T. grandis* plantation and clarify what could be the realistic rates of interests to be used in such investments. In addition we review how the previously suggested management regimes look from the economic point of view by implementing them in the model of our study. In this thesis we maximize the bare land value by optimizing the thinning and final cut regime of *T. grandis* plantation in Costa Rica. Costa Rica was chosen, because it was the only country that had an existing statistical growth model created for *T. grandis* that could be used for economic optimization.

1.1 *Tectona grandis* as a commodity and its growth characteristics

The characteristics of *T. grandis* are its good strength and weight. *T. grandis* as a raw material is considerably easy to process and the sanded wood is easy to polish (de Vriend 1998, p.18). The heartwood of *T. grandis* is considered more valuable, because of its darker brown color and higher dry density. One of the most important reasons why *T. grandis* is favored especially in outdoor use is its superior weather resistance (de Vriend 1998, p. 23). On the other hand the lower quality *T. grandis*, containing parts of sapwood, needs plenty of care and is mainly suitable for interior use.

As the proportion of heartwood content is highly desired, it inflicts the determination of the value of *T. grandis*. Few studies discuss if a higher proportion of heartwood may be achieved through different management practices and by choosing the right site for the plantation (see e.g. Morataya et al. 1999, Thulasidas et al. 2006). Previous studies suggest that heartwood proportion growth is in relation to aging and DBH growth causing the sapwood to turn into heartwood (Pérez and Kanninen 2005b). In addition the soil aridity has been considered as a significant factor affecting to the heartwood content (Pérez and Kanninen 2003b, Thulasidas et al. 2006). The native environment of *T. grandis* has a distinct dry and rain season, which it requires anywhere it is being planted. Planted *T. grandis* timber has in general a lower price in the markets than its natural counterparts in Asia due to color variations and smaller log sizes. There are some counter arguments against increasing growth of basal area through heavy thinning. As this method clearly enables more rapid diameter growth, some studies argue that a large canopy of the tree may lead to larger sapwood content as the canopy growth requires higher sapwood content and therefore accelerates the growth metabolism of sapwood (Bamber 1976). Some practical experiments have been carried out in an attempt to increase the heartwood content by cutting the top of the tree off from trees that have passed their best growth in diameter in order to reduce the living sapwood share inside the tree (Kanninen 2012).

T. grandis plantations are considered as fairly labor intensive in comparison to other plantation species. The trees need pruning, but allegedly also intensive thinning from very early on. Pérez and Kanninen (2005a) have done a thorough research concerning ecological modeling and implementing different forest management scenarios to Costa Rican *T. grandis* plantations. The selection of trees in thinnings has in practice been based on the growth and form of individual trees so that the dominant trees with well-formed crown are left and competitively inferior or malformed trees are removed (Pérez and Kanninen 2005b, Seppänen 2012). In practice this resembles thinning from below. It will be later discussed why an alternative approach might be economically preferable.

T. grandis plantations are widely spread throughout tropical regions and can be found from Africa, Asia, and South and Central America (Kollert and Cherubini 2012). The largest amount of *T. grandis* plantations were reported to be in Asia, in countries such as India, Indonesia and Thailand. In South and Central America *T. grandis* plantation area is growing rapidly. It is worth noting that in general *T. grandis* is faster growing and more intensively managed in Africa and Latin America than in most Asian countries where the species is cultivated. *T. grandis* is one of the most cultivated hardwood species for timber production in the world. The estimated global area of *T. grandis* plantations, excluding 22 minor *T. grandis*-growing countries, was 4.3 million hectares in 2010 (Kollert and Cherubini 2012). According to their report a major part of this was in Asia, 82.8 %. A large part of Asian plantations are planted through government programs. Historically the *T. grandis* plantations in these countries have been managed with excessively long rotation periods, 60 years or more (see e.g. Jayaraman and Rugmini 2008, Kollert and Cherubini 2012). The largest trend in establishing *T. grandis* plantations in Latin America has happened in Brazil, which has intensive management of the plantations and the latest genetic and mechanized technologies improving the stand growth, timber quality and reducing costs. *T. grandis* planting has developed well in Central American countries such as Costa Rica and Panama. Kollert and Cherubini (2012) reported that there were 31 500 ha of

T. grandis plantations in Costa Rica in 2010. In comparison according to Brazilian Association of Planted Forests Producers (2013, p. 101) there are 67 329 ha of *T. grandis* plantations in Brazil.

From environmental perspective the existence of monocultural forest plantations should be considered as a choice in landscape management among other land uses. This option is reasonable when the net present value of such forest plantation exceeds the net present value of competitive land uses. In order to make such evaluation one may need to consider, in addition to the economic values, the environmental and social values and their impacts. *T. grandis* may have environmental impacts by sequestrating carbon during the rotation, and additionally in the end products. The monocultural nature of *T. grandis* plantations can be considered as a negative environmental effect if it reduces the biodiversity in the area where it is being planted. Although quite commonly in Latin America *T. grandis* plantations are established on abandoned arable land and therefore the impact of such monoculture plantation is more likely to be neutral or even positive (Pagiola 2008). In addition to providing timber, the plantations may take pressure off from natural forests. The economic theory suggests that as the plantation area expands the low cost of plantation timber, in relation to timber from natural forest, thus making the logging of natural forests unprofitable. This would lead the markets to change into using plantation timber instead, and hence would encourage the expansion of forest plantations (Cossalter and Pye-Smith 2003). Even though it sounds logical to say that plantations take some pressure off natural forests, it is still more notable that in many cases it is the population growth driven by agricultural and mining activities that lead to deforestation in natural forests.

1.2 *Tectona grandis* markets

The plantation *T. grandis* is displacing in some extent the natural *T. grandis* in the global market. Because of the superior characteristics and therefore high value of natural *T. grandis* it is still being illegally logged (Kollert and Cherubini 2012) even though its imports are prohibited in United States (The Lacey Act Amendments of 2008) and Europe (Regulation (EU) No 995/2010). The average price of plantation grown *T. grandis* is still increasing in the global market, mainly due to the scarcity of natural *T. grandis*. Because of the booming interest to invest and grow *T. grandis* this trend could equilibrate in upcoming years. The prices of planted *T. grandis* timber are notably lower than the prices of natural *T. grandis*, because of its young age and claimed inferior quality (de Vriend 1998, p. 26). Nevertheless there is currently a high demand of *T. grandis* timber at the global markets compared to what producers can supply. The natural *T. grandis* timber comes dominantly from Myanmar. The natural *T. grandis* is often, if not always, illegally and unsustainably logged from partly natural forests (Myint 2012). There is international pressure to salvage the natural *T. grandis* forests, which are usually pristine tropical forests that encompass a multitude of biodiversity. Because of the previously mentioned reasons, the natural *T. grandis* timber has become more expensive and this has directed the interest towards *T. grandis* plantations.

In addition, the change in mentality towards environmental awareness, which has risen considerably in just few decades due to the so called “*green revolution”*, may help to increase the global demand of quality sawnwood timber such as *T. grandis*. Wood is considered as the eco-friendly construction and furniture material as it is biodegradable and sequestrates carbon. Normally wood requires less chemicals and energy to produce than rival nonrenewable raw materials (Petersen and Solberg 2005). Figure 1 illustrates how the average spot price of imported plantation *T. grandis* logs has developed since 2010. Although the time range is short there is a strong trend in price increase. The main reason for the plantation *T. grandis* price increase is the declining supply of natural *T. grandis*.

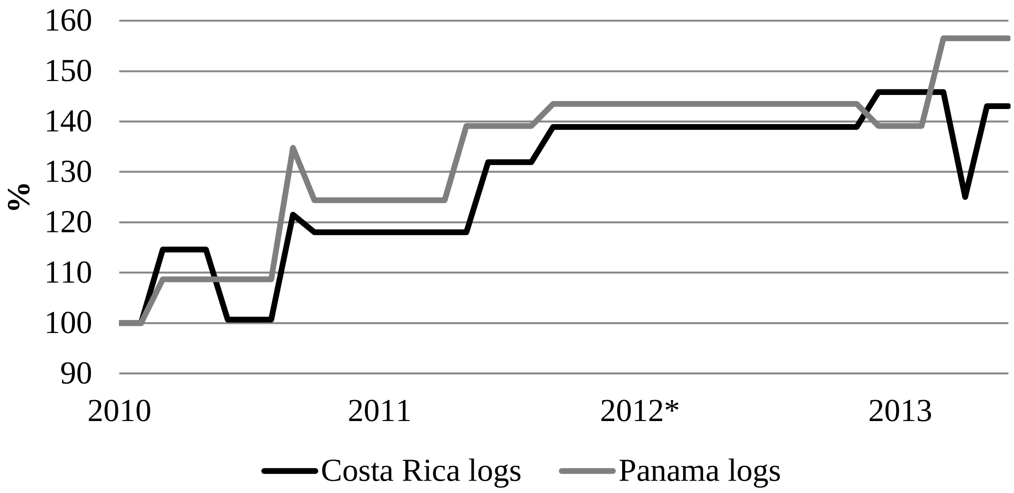

Figure 1. Monthly plantation log price index, February 2010 = 100 (ITTO 2013). *2012 figures were not available.

1.3 *Tectona grandis* in Costa Rica

T. grandis has been extensively studied in Costa Rica, mainly in University of Costa Rica in San Jose and Centro Agronómico Tropical de Investigación y Enseñanza (CATIE). The studies are usually related to the genetics of *T. grandis.* In 1970s and 1980s Costa Rica had fastest deforestation rates in the world, 30 000 to 50 000 hectares annually (de Camino et al. 2000, p. 1) . Costa Rica started to subsidize forestry in 1977 in an attempt to reforest the deforested land (de Vriend 1998, p. 33). The subsidy caused many farmers to plant *T. grandis* only in order to get the subsidy payment. These plantations were quite often poorly managed and the lack of management caused malformation of tree trunks in such plantations. The subsidization ended in 1996 by the time USD 100 million worth of subsidies had been paid for reforestation (de Camino et al. 2000, p. 52). Subsidies caused at least two negative effects; they gave an image of forest sector being poor state-dependent sector, and secondly resulted in focus entirely on wood production neglecting all the other forest services. According to de Camino et al. (2000) the environmental services need to be subsidized in Costa Rica, as otherwise landowners would mine their forests and convert their lands to other uses. In general it is suggested in economics that subsidies should not be paid for business activities that have established and well-functioning markets. In case a business activity could be producing more positive externalities (e.g. carbon sequestration) then a subsidy could be justified. In line with the above reasoning a payment for environmental services program (PPSA) was introduced in the beginning of 1997 after the programs targeting at reforestation in Costa Rica (Pagiola 2008). The program is funded by the National Forestry Financing Fund (FINAFIFO).

Historically *T. grandis* has been cultivated in the lowlands of four regions in Costa Rica: the Atlantic Zone, the Northern Zone (or Zona Norte), Guanacaste and Central and South Pacific (de Vriend 1998, p. 35). These regions can be divided into two main production areas, being the Pacific lowlands consisting of Guanacaste and Central and South Pacific, and the Atlantic lowlands, including the Northern Zone and the Atlantic Zone. The distinction to these two areas is made on the basis of the most important requirement of *T. grandis* - the length of the dry season. The Pacific lowlands have a distinctive dry season of 3 to 7 months, whereas the Atlantic lowlands have a dry season of 1 to 2 months.

1.4 Previous studies

The overall functionality of optimizing even-aged forests have been proven in several previous studies and one of the earliest studies with thinnings included was by Haight (1987). He studied the optimal sequence of harvesting and planting on achieving steady-state management for *Ponderosa pine*. In our study the objective is to find the locally optimal solution in the management regime that maximizes the bare land value.

1.4.1 Economics

A forest stand and the land are considered as a capital for which a forester can calculate the opportunity costs. A forester needs to consider those incomes or benefits that the operating capital in forest would achieve in the best alternative same risk-level investment choice. In our study we aim to calculate the bare land value of *T. grandis* plantations, which may be used in comparison to alternative land uses. The comparative statics in our study are carried out by executing the optimization calculations with various rates of interests and with price adjustments.

As an example, a study by Griess and Knoke (2011) showed that in Panama the local species may have even more rapid growth projections in plantations and yield higher net present values, over twofold, compared to *T. grandis*. They found a net present value per hectare to be 13 267 USD ha^{-1} with 5% interest rate and with a rotation time of 25 years. The growth was based on the study by Pérez and Kanninen (2005b). The above result is also in the same scale as the other previous studies mentioned in our study. On the other hand the study does not take into consideration the available information and ease of cultivating *T. grandis* species. The information available on managing *T. grandis*, its good timber characteristics and its relative indifference of the growing environment's characteristics favors its use as a plantation species. In fact different kind of results were obtained from a similar study carried out in Costa Rica where mortality and yield rates of 13 native species were compared to *T. grandis* (Piotto et al. 2004). The study shows that only one native species *Schizolobium parahyba* exhibited higher growth than *T. grandis* and ten species exhibited notably higher mortality rates than *T. grandis.*

The previous economic studies consist of mainly net present value calculations. Puolakka (2003) discussed in his Master's thesis the profitability of Costa Rican plantations as a case study of two existing plantation enterprises. His study contained NPV and IRR calculations. The rotation time used in his calculations was set to 24 years. Examined interest rates varied from 0% to 9% with company A and from 0% to 22% with company B. For example with interest rate of 5% the NPV for company A was 7 187 USD ha^{-1}, and 19 895 USD ha^{-1} for company B. The average of the above figures (13 541 USD ha^{-1}) is in line with the results from more recent studies. The IRRs found were 7.49% and 19.42% respectively. At a glance one may observe that the IRR for company B seems excessively high.

Pérez (2005) studied stand growth for *T. grandis* plantations in Costa Rica for his academic dissertation. He also conducted a financial analysis where he calculated net present value (NPV) and internal rate of return (IRR). The analysis was carried out for three different types of site classes when the objective was either to maximize diameter at breast height (DBH) or volume, and the applied rotation time was either 20 or 30 years. He used the interest rates of 5%, 7.5% and 10%. For example, for site class I when the objective was to maximize volume with a 20 year rotation the net present value per hectare with the above interest rates were 34 814 USD ha^{-1}, 21 662 USD ha^{-1} and 13 415 USD ha^{-1}, respectively. IRR obtained in this case was 22.6%.

1.4.2 Forest management

In plantation forest management the key decisions involve the timing, the number and the intensity of thinning(s) as well as the final cut timing. The factors affecting these decisions commonly are the biological growth, the prices and costs in relation to the wood characteristics and size, and the rate of interest. In some cases the management objective is to maximize the volume production of the stand, which is economically unjustified except in some rare conditions such as zero rate of interest. Thus it is no more justified from an economic point of view to maximize the volume, but instead the net present value.

Insufficient knowledge about the heartwood proportion growth and its impact on the log price makes the valuing of *T. grandis* plantation problematic. The previous studies found a no significant relationship between thinning intensity or timing, and the heartwood content (Pérez and Kanninen 2005b). Pérez and Kanninen (2005b) found that moderate and heavy thinning yielded the highest heartwood proportions and light thinning yielded higher average values, but this was more because of the size and dominance of the left trees rather than correlation with the treatment itself. The results were surprising as it had been previously thought that trees in dense stands have less crown area and grow slower, therefore requiring less sapwood which would lead into higher proportion of heartwood as suggested by Bamber (1976). Pérez and Kanninen (2003b) suggest that the heartwood proportion grows mainly with increasing DBH.

The rotation lengths used for *T. grandis* plantations vary throughout the globe. Kollert and Cherubini (2012) found rotation lengths from 6 to 30 years to be applied in Central America. Evans and Turnbull (2004) found *T. grandis* plantation rotation length to vary from 10 to 22 years in Central America. Pérez (2005) studied different growth scenarios under different thinning regimes. The aim was either to maximize the stand volume or the diameter at breast height growth. The study resulted in five thinnings at highest with intensities from 20% to 50% timing at the ages of 4, 8, 12, 18 and 24 years. The rotations in the study were 20 and 30 years and the site was either low, medium or high quality. In addition to previously mentioned studies other growth modeling for *T. grandis* have been done by Pérez (2008), and Bermejo et al.

(2004) in Costa Rica. More detailed comparison to these studies is made in the discussion chapter.

T. grandis plantations, as well as any other tropical forest plantations or forest asset in general, require effort in risk aversion. The common risks in *T. grandis* plantations are fire, storm, pests (especially ants) and diseases (de Vriend 1998, p. 37). To avoid or lower these risks, preventive measures are taken in *T. grandis* plantations. The chance of these risks is higher in the early phase of the stand rotation as the young seedlings are not strong enough to resist such risks naturally. Therefore insecticides and fire lanes for fire control are usually applied in *T. grandis* plantations, and consequently the plantation silvicultural costs are very high in the early phase of the rotation. Another substantial silvicultural cost in the early phase is created from the pruning of the trees which ensures that the tree's lower trunk is knot-free in the later phase. Pruning also creates a risk to the tree as it may cause damage and *T. grandis* is slow to heal from such treatment. As a result pruning needs to be carried out with caution.

There are other ways to manage forest without applying a traditional even-aged rotation type of forest management, e.g. uneven-aged forest management. *T. grandis* plantations are by definition planted, but if the regeneration of the forest could be accomplished with natural regeneration then the optimization problem could concern uneven-aged forestry and optimal steady state management. The benefits from uneven-aged forestry would come from nonexistent or low replanting costs and environmental benefits from keeping the land forested infinitely or for very long periods of time. In addition possible preferences in the size of logs or in the density of annual rings, indicated by higher prices, could be taken into consideration when using selective harvesting, instead of the more homogenous procedures used in even-aged forest management. Currently even-aged forest management is suitable and easily implemented for forest plantations due to the monocultural nature in forest plantations, which allows linear planting, thinning and clear cut regimes with high efficiency. The alternative forest management models are not discussed here, but it is still important to acknowledge that such management alternatives exist, and may even be economically more optimal under a different setting (Tahvonen 2009).

1.5 Objective of the study

The objective of our study is to optimize the rotation time in order to find the economic optimum, which maximizes the present value of net revenues in *T. grandis* plantations. Determining rotation time in forestry is one of the most important economic decisions. Acknowledging the rotation time helps to maximize the net present value, and in this case the bare land value.

Objective of our study is not to analytically describe and solve the used model in its full detail, but to give a numerical example how the model may be used in practice. For detailed analytical solution see e.g. Getz and Haight (1989). Faustmann model (1849) has been shown in various studies to be the most sensible theory to solve the economic optimum in even-aged forestry (Samuelson 1976, Haight 1987). However, the growth of *T. grandis* even under plantation conditions still contains plenty of complexity, e.g. heartwood proportion growth, which creates unavoidable bias in our study.

Altering the interest rates, the wood price, the harvesting costs, the site class and initial stand size in a set range of variables, the optimization model should result in different thinning regimes, rotation lengths and bare land values under those conditions. What separates our study from the previous *T. grandis* related studies is the inclusion of economics when attempting to optimize the rotation and thinnings with mathematical computing software. If the results withstand scrutiny they should ultimately help plantation managers in their decision-making process. The reader should stay aware that the statistical growth model used in our study is location specific to Costa Rican plantations.

When planning a plantation project there may be considered three main steps that outline the overall plantation design (Evans and Turnbull 2004, p. 90-104). First step is plantation identification, which includes analysis of the project environment and creation of plantation proposal. For example, analyzing the national policies, possible risks, adoption of standards and guidelines, and identifying environmental effects. According to Evans and Turnbull (2004) the typical timeframe for a strategic plan is two or more rotations. Second step is the project appraisal, which includes an in-depth analysis of the related information, e.g. feasibility studies based on information on land tenure, land-use, and land cover, physical features of the land, ecology, socio-economics, legislation and policies, and infrastructure. It is pointed out that in a plantation project it is especially important to obtain and analyze the data of likely growth rates for the main species. Third step, if still justified after considering step two, is the implementation of the project in the best possible manner. Evans and Turnbull (2004) consider the following: “(i) design of the project; (ii) preparation of a management plan; and (iii) preparation of impact statements and design of environmental monitoring systems and audits.” This paper is linked in particular to the second step and intends to rationalize further the decisions to be made in a *T. grandis* plantation project.

The hypotheses of this thesis are:

1. The optimal rotation length in *T. grandis* plantations is different than what is commonly suggested for *T. grandis* plantation management in Costa Rica.
2. The optimal number, timing, and intensity of thinnings vary due to multiple reasons.
3. Changes in price will notably affect the end results.
4. Heartwood content changes the plantation management regime. Heartwood content in relation to diameter at breast height will lengthen the optimal rotation time.
5. Descriptive theory outcome; what *does* happen. What happens when *T. grandis* plantation regime is optimized?
6. Normative theory outcome; what *should* happen. What kind of policies or silviculture recommendations should follow from the optimization results?

2 METHODS AND MODEL

The method to analyze the optimal rotation time of *Tectona grandis* is to use the Faustmann formula, which is connected to the ecological growth model. The ecological model, the economic objective function and the necessary constraints are encoded with algebraic modeling language (AMPL), which is then implemented in KNITRO solver.

Faustmann model is modifiable and useful from both theoretical and practical point of view when maximizing the economic benefit of even-aged tree stands. The Faustmann model has been proven analytically correct for the purpose of optimizing an even-aged stand (see e.g. Haight 1987). Faustmann formula may be extended to take into account several other factors, e.g. intangible benefits or carbon sequestration. The model used in our study does not consider uncertainties, for example changes in the price in the future or government subsidies. For the purpose of seeing the effects of a price increase or decrease a separate sensitivity analysis is carried out.

First the objective is to calculate the optimal rotation length without thinnings. Further the objective is extended by including thinnings to optimize the number of thinnings and rotation length. The model is then solved with two different initial planting densities, 1111 and 816 trees, denoting a spacing of 3m x 3m and 3.5m x 3.5m, respectively. The rotation length is chosen according to the highest bare land value attained with each optimization. The number of allowed thinnings is manually selected by increasing the number of possible thinnings. When the bare land value does not increase anymore when increasing the number of thinnings and the optimization does not deploy available thinnings in order to avoid the fixed thinning costs, then the optimal number of thinnings is found for the specific site characteristics with given attributes. The highest bare land value result after the discounted fixed harvest costs are subtracted. A sensitivity analysis is carried out with different rates of interest and by varying price with plus 20% and minus 20%. A simple ad hoc test is made to illustrate the possible effects the heartwood proportion growth may have on the optimal solution through consequent changes in price. Finally, a comparison is made with preset management regime suggested by Pérez and Kanninen (2005a).

2.1 Model

The following equations form the stand growth of *T. grandis* based on parameters determined in Costa Rica. The parameters are indicated with indexed alphabets. The decision variables are the intensity of thinning, timing and number of thinnings and rotation length.

Let t denote the time in the model, $t = 0, \dots, T$, where T is the final cut time. The number of thinnings is denoted by $i = 1 \dots k$. Variables for thinning intensities as a share of logged trees (H) from total number of trees in stand (n), respectively:

$$H_t \geq 0 \tag{1}$$

$$n(t) \geq 0 \tag{2}$$

The number of trees is subject to a constraint where the number of dead trees and harvested trees are subtracted from the trees of current period in order to model the trees available for the next period, $n(t+1) = n(t) - n(t)\mu(t) - n(t)\sigma(B) - H_t n(t)$. The initial number of trees in the beginning of the rotation is fixed, $n(0) = 1111\ or\ 816$.

Both height and diameter growth are Chapman-Richards functions (Richards 1959, Chapman 1961). Equations for the dominant diameter at breast height (DBH) and dominant height growth as a function of time (Pérez 2005), cm and m, respectively ($a_1 = 60, b_1 = 0.07, c_1 = 1.165, a_2 = 35, b_2 = 0.09, c_2 = 1.1$):

$$d(t) = a_1(1 - e^{-b_1 t})^{c_1} \tag{3}$$

$$h(t) = a_2(1 - e^{-b_2 t})^{c_2} \tag{4}$$

Equation for the stand basal area as a function of time, $\mathrm{m}^2\mathrm{ha}^{-1}$:

$$B(t) = \frac{\pi[\frac{D(t)}{2}]^2\ n(t)}{10\ 000} \tag{5}$$

The growth modification factor, i.e. competition factor, represents the proportional overall competition over the available resources between the trees in the stand annually. Equation for the growth modification factor as a function of stand basal area (Pérez 2005) ($a_3 = 0.003, b_3 = 0.16$):

$$z(B) = 1 - [a_3 e^{b_3 B(t)}] \tag{6}$$

The competition modified diameter at breast height growth variable $D(t) \geq 0$, can now be determined through a constraint $D(t+1) = D(t) + g(t)z(B)$, where $g(t)$ is the current annual increment denoted as a constraint, $g(t+1) = \ d(t+1) - d(t)$.

Equation for the proportion of tree mortality as a function of age and as a function of basal area, which both must satisfy non-negativity constraints ($a_4 = 0.0051,\ b_4 = 0.015,\ \ a_5 = 0.003,\ b_5 = 0.11$):

$$\mu(t) = a_4 e^{b_4 t} \tag{7}$$

$$\sigma(B) = a_5 e^{b_5 B(t)} \tag{8}$$

The parameter b_7 represents in the total merchantable volume function (10) the upper stem merchantability limit. The volume is calculated outside the bark. Equations for the total and merchantable volume growth (Pérez and Kanninen 2003a), $\mathrm{m}^3\mathrm{ha}^{-1}$ ($a_6 = 0.00878, b_6 = 0.00003251, a_7 = 0.7839, b_7 = 11.99, c_7 = 2.4149, d_7$=-2.4175):

$$Q(t) = a_6 + b_6[D(t)^2]h(t)n(t) \tag{9}$$

$$V(t) = Q(t)[1 - a_7 b_7^{c_7} D(t)^{d_7}] \tag{10}$$

A polynomial function was created from the price data. The wood price is restrained with an if-else condition so that the wood price obtained a zero value when the diameter at breast height is less than 13 cm. The justification for this constraint is that *T. grandis* has no commercial use and therefore no value in such small sizes due to the dominating sapwood and bark content. The wood price function which depends on the average diameter at breast height in the stand, USD m^{-3} ($a_8 = -0.0039$ $b_8 = 0.502,\ c_8 = -10.513,\ d_8 = 116.388$):

$$p(t) = a_8D(t)^3 + b_8D(t)^2 + c_8D(t) + d_8 \tag{11}$$

The thinning cost function is restrained with an if-else condition where the thinning cost is considered zero with diameter at breast height being less than 13 cm. Thus the only cost from thinning small trees is the fixed harvesting cost. The thinning cost function which depends on the average diameter at breast height in the stand, USD m^{-3} ($a_9 = 106.027$ $b_9 = -0.0714$):

$$C(t) = a_9e^{-b_9D(t)} \tag{12}$$

The continuous time discount factor is denoted as e^{-rt}. When harvesting is positive fixed costs occur, $H(t_i)> 0 \rightarrow C_{fixed}$. The fixed costs consisting of periodical silvicultural as well as the planting costs and fixed costs C_{fixed} from harvesting, USD ha^{-1}:

$$W = \sum_t -w(t)e^{-rt} + \sum_{i=1}^{k} C_{fixed}e^{-rt_i} \tag{13}$$

What strategy is optimal depends greatly on how the objective function is specified. In our study the objective function for maximizing the value of the bare land under thinnings, where W is the fixed silviculture costs, USD ha^{-1}:

$$\max_{\{T,k,n_0,H_{t_i},t_i,i=1,\dots,k\}} BLV = \frac{W + [p(T) - C(T)]V(T)e^{-rT} + \sum_{i=1}^{k}\{[p(t_i) - C(t_i)]V(t_i)H_{t_i}e^{-rt_i}\}}{1 - e^{-rT}} \tag{14}$$

The optimization codes applied in this thesis are shown in Appendices 1-3.

2.2 Data and location

In the target country, Costa Rica, the climate and therefore the soil is highly moist throughout the year. Costa Rica, situated between the Caribbean Sea and the Pacific Ocean, has an annual precipitation ranging between 1500 to 6000 mm. The number of dry season months (rainfall less than 100 mm) differs regionally and ranges between 0 to 6 months while the average dry season is 3.5 months. The above mentioned length of dry season is based on the data from the 11 regions studied for creating the statistical model (Pérez and Kanninen 2005a). In those areas that were studied the annual precipitation varied between 1659 to 4107 mm.

Costa Rica may have lower efficiency on *T. grandis* plantations than some other countries producing *T. grandis* in Latin America, such as Brazil. The Costa Rican *T. grandis* plantations are usually not large industrial plantations and hence lack investments for mechanization (Seppänen 2012).

The statistical growth model used in our study is from the previous studies by Kanninen and Pérez (Pérez 2005). Several plantation specialists were consulted in order to fine down different elements in the model and to limit down the model to a generic plantation stand in Costa Rica (Kanninen 2012, Seppänen 2012).

2.2.1 Price data

The price structure of the timber changes by gradations as the tree achieves specific wider diameters. Also the value of heartwood is considerably higher than the value of sapwood, making the valuation of the total volume less accurate. Heartwood content is typically more apparent the older the tree is. Therefore ideally both diameter and age affect the price of *T. grandis*. In addition the increase in stem height has a decreasing effect on the heartwood proportion and also the site wetness has a statistical difference on heartwood proportions as trees on dry sites have a higher heartwood proportion (Pérez and Kanninen 2003b). In our study we rely on using the aggregate price data provided.

The prices used in our study are to be considered as exemplary as the price of *T. grandis* is not efficiently monitored. According to a *T. grandis* plantation specialist

Seppänen (2012) the price of *T. grandis* roundwood develops almost linearly between the log diameters of 13 cm to 41 cm from 115-435 USD m^{-3} (

Table 1). The prices used in our study are log prices from the final felling. Before reaching DBH of 13 cm the roundwood has a little value as energy wood. In our study the price is considered as zero before reaching values over 13 cm at diameter at breast height. The early prices attained start from around 50 USD m^{-3}, which represents the value for making poles or joinery products with small heartwood proportion. After DBH of 45 cm the price could in some cases increase strongly due to unique customer preferences, such as preferences in the color of the wood or dense annual rings. This element of uncertainty in the price fluctuation is not included in the polynomial price function used in our study.

Prices available were roadside prices of logs. The linkage between log prices and the diameter at breast height was created by taper function (Indufor 2006). The bucking was carried out so that the logs attained a length of 4.6 meter and had a maximum upper diameter of 14 cm. The volume weighted average of these logs was taken to represent its own DBH-class. In the taper function DBH-classes from 25 to 47 cm were used, which were based on 6, 12, 17 and 26 year old trees.

The possible effects of the heartwood proportion to the tree value and the following consequences to the optimal management were tested separately. No public information on the heartwood proportion in relation to *T. grandis* price was found. It is commonly considered that high heartwood proportion and high dry density are the most desired wood characteristics for *T. grandis* (Tewari 1992, Bailleres and Durand 2000). In order to roughly highlight the possible effects of heartwood proportion growth the equation (15) from Pérez's and Kanninen's study (2003b) was used to represent the heartwood content as a function of DBH. Then the proportion was used for multiplying the price function. This test was carried out to study if the heartwood proportion growth has a significant effect on the optimal management. The log prices, such as the prices used in our study, are usually reported by the log diameter without indicating the heartwood proportion in the logs. The log prices usually refer to the prices in the final felling where the heartwood proportion is very high (around 50%). The problem with this test is the absence of interrelation between stand density and canopy growth and other consequences related, which are discussed further in the discussion part of this thesis. To take into account the sapwood content, a scaling parameter was chosen to multiply the price function. The parameter was chosen on the basis of common practice in Costa Rica where the final felling is carried out around the age of 20 when the DBH achieves roughly 40 cm. Therefore we scaled the heartwood proportion modified price to be identical with the baseline price at DBH of 40 cm. This resulted in a scaling parameter value of 2. The heartwood proportion (Pérez and Kanninen 2003b) ($a_{10} = -92.974, b_{10} = 90.012$):

$$HW(t) = a_{10} + b_{10}\log[D(t)] \quad (15)$$

Table 1. Road side prices for different diameter logs, over bark, USD m^{-3}.

Log diameter (cm)	Price
13-19	115
19-25	185
25-31	285
31-37	375
37-41	435

2.2.2 Cost data

The silvicultural cost structure of the stand may vary heavily between different plantation locations. The better the location, behalf of its growing conditions for the trees, the less there is need for human intervention, e.g. fertilization. Puolakka (2003) found that the establishment costs had minor difference between the two companies that were observed in his study, and that the silvicultural labor costs were almost identical. The overall cost structure for the companies were significantly different. This was mainly due to high administration fees, land prices, infrastructure costs and farm costs for the other company. Site selection depended on climate, soil, drainage, accessibility and distance to port. If the soil has an inferior drainage then this can be modified with soil cultivation. Existing land use has an effect on site clearing costs and on certification. Initial stand size, and selecting either clones or seeds have effects on the costs. According to the interviewed *T. grandis* plantation specialist Seppänen (2012), planting with clones requires fewer trees in the initial stand and is argued to have a better yield and a shorter rotation as well (see also Isotupa and Tyynelä 2010). Fertilization is not of great importance, but it is still used on inferior sites to ensure the growth. Weed control is considered essential for the first three years. After this period the canopy closes and prevents weed growth. Insect control is applied if necessary. Often a prevention of fire hazards is implemented according to the site preferences and prevention of wind hazards in the early stages of the plantation (from 1 to 3 years) by supporting the trees up.

In our study the costs are comprised of site preparation, establishment and plantation maintenance costs (Table 2). In email exchange with a *T. grandis* plantation specialist a range of silvicultural costs were defined suitable for a generic *T. grandis* plantation in Costa Rica with intensive management (Seppänen 2012). The assumptions are that the land is grassland and all the silvicultural works are outsourced. Site preparation includes such procedures as elimination of disadvantageous vegetation, forestry plough, construction of roads and fences and production of seedlings. The establishment costs include such elements as weed control, transportation of seedlings, planting, re-planting and marking the seedlings and fertilizing. The plantation maintenance costs include such elements as singling, pruning, sprout cleaning, post-planting weed control and other costs.

The only difference taken into consideration in silviculture costs between 816 and 1111 planting is the costs of the seedlings. The total costs for 898 seedlings for planting 816 seedlings were 224.4 USD ha^{-1}. The total costs for 1222 seedlings for planting 1111 seedlings were 305.5 USD ha^{-1}. Other silviculture costs were kept fixed.

The fixed harvest costs from mobilizing the work force and marking the trees were estimated to range from 350 to 650 USD ha^{-1} per single visit to the stand for harvest operation (Seppänen 2012). Therefore per hectare cost was determined to be the lowest value of this range as it is imprecise how large area may be thinned or harvested simultaneously with one visit and how long and difficult the route to plantation is. Neither was stand density taken into consideration as it was unclear in which direction and to what extent it would alter the fixed harvest costs. If fixed harvest cost is not targeted to a harvest the tests showed that the optimal solution would have been to execute thinning annually and most of the thinnings would be extremely light, i.e. fine tuning of the growth.

The harvesting costs vary according to the stand average DBH. Determining the harvesting costs is problematic due to discrepancy in harvesting methods used in variety of sites. In Costa Rica plantations are usually harvested by hand, using cables, chainsaws and a farm tractor. The early pre-commercial harvesting costs were 0 USD m^{-3} in our study, if harvesting happens before a stand average DBH of 13 cm has been reached. However, fixed harvest cost will still occur normally. The harvesting costs used in our study and presented in Table 3 were obtained from a *T. grandis* plantation specialist (Seppänen 2012).

Table 2. Exemplary silvicultural plantation costs per hectare used in our study for initial planting density of 1111 trees, USD ha^{-1}.

	Year									
	0	1	2	3	4	5	6	7	8	9…T
A) GRASSLAND SITE PREPARATION	**71**									
1. Elimination of individual trees	25									
2. Grass burning	45									
3. Elimination of fences	6									
B) SOIL PREPARATION	**260**									
C) ACCESS ROADS	**625**									
D) FENCING	**24**									
E) PLANT PRODUCTION	**306**									
F) PLANTATION ESTABLISHMENT	**183**									
1. Pre-plantation weed control, herbicide	14									
2. Pre-plantation weed control, application	50									
3. Transport of seedlings	40									
4. Planting and marking	78									
5. Re-planting	1									
G) FERTILIZATION	**161**	**40**								
1. NPK fertilizers	50	12								
2. NPK application	106	27								
3. Local transport	5	1								
H) POST-PLANTING WEED CONTROL	**550**	**297**	**228**				**100**	**100**	**100**	**100**
1. Manual slashing	550	90	90				100	100	100	100
2. Herbicides post-planting		42	28							
3. Herbicide application post-planting		165	110							
I) PRUNING		**98**	**98**	**65**	**65**	**65**	**65**	**33**	**33**	
1. Singling		33	33							
2. Pruning + sprout cleaning		65	65	65	65	65	65			
3. Sprout cleaning								33	33	
J) OTHER COSTS	**50**	**50**	**50**	**10**	**10**	**10**	**10**	**10**	**10**	**5**
TOTAL	**2229**	**485**	**376**	**75**	**75**	**75**	**175**	**143**	**143**	**105**

Table 3. Aggregate harvesting costs, USD m^{-3}.

Stand avg. DBH (cm)	Cut + de-branch	Crosscut	Forest transport	Sub-total	Supervision	Total
15	13.3	2.0	17.3	32.6	4.9	37.5
20	5.5	1.4	13.0	19.9	3.0	22.9
25	2.5	0.7	10.4	13.6	2.0	15.6
30	1.2	0.5	8.7	10.4	1.6	11.9
35	0.9	0.4	7.4	8.7	1.3	10.0

2.2.3 Interest rate

Previous studies apply interest rates between 1% to 15%. The annual real lending interest rate in Costa Rica has been on average 11.22% during 2000 to 2012 (World Bank 2013). World Bank defines the real interest rate as "*the lending interest rate adjusted for inflation as measured by the GDP deflator.*" The highest real interest rate of this period was in 2000, being 16.74%. The lowest real interest rate was 3.04% in 2008 as shown in Figure 2. For years 2007 to 2012 the real interest rate averaged 8.38%. According to Cubbage et al. (2010) the risks in Latin American forest plantations are considered high and therefore preferred real rates of return for investments are very high. In this thesis we used real interest rates of 5%, 7.5%, 10% and 12.5%. When results are compared to other studies we use mainly rate of interest of 5% as this rate has been used in most studies to illustrate the results.

The reason why high rate of interests are applied is the several risks that are involved in *T. grandis* plantations in Latin America. The risks include ecological, political, social and economic risks. Ecological hazards are e.g. fire, pests or diseases. Political risks are e.g. wars, revolutions or currency shortages. The political climate may change to support different kinds of land uses diminishing the investment on *T. grandis* plantations. The social hazard may involve conflicting interests between local communities and *T. grandis* plantation owners on behalf of the land use. The economic risk includes such factors as instability in wood and labor prices. Another economic risk is a strongly fluctuating real rate of interest creating instability for investors seeking funding in Costa Rica for *T. grandis* investment. This might not be a direct risk to international investors who seek their funding from other countries than Costa Rica.

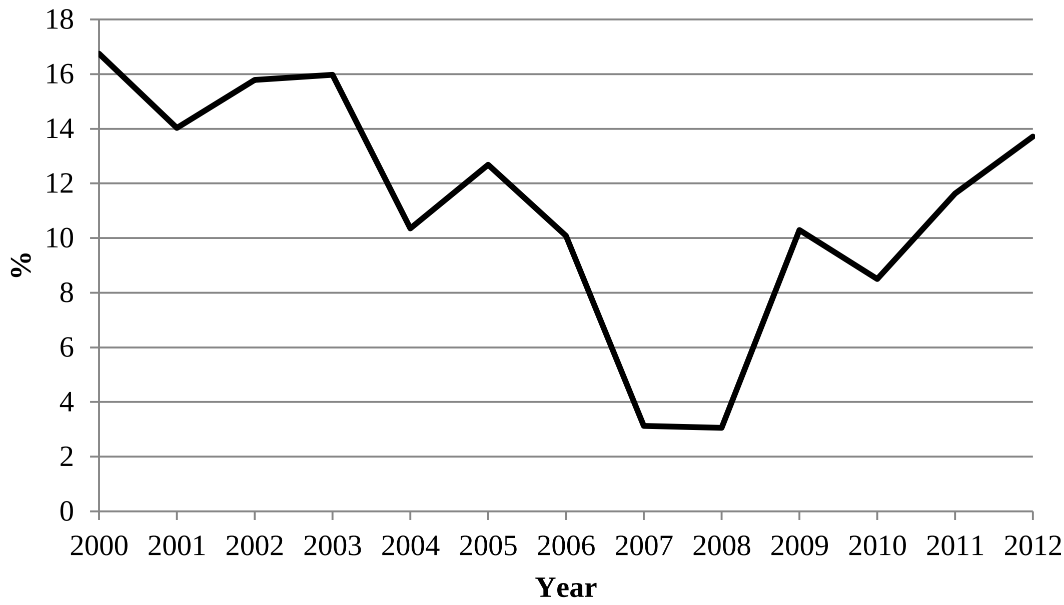

Figure 2. Real rate of interest in Costa Rica from 2000 to 2012 (World Bank 2013).

2.2.4 Growth data

In our study growth parameters from Pérez and Kanninen (2003a) are used for solving of the model. Parameters for mortality as a function of basal area and time were obtained from Kanninen (2000).

Diameter growth modification equation (6) represents the competition between trees as a function of basal area. Intuitively this embodies the scarcity of resources the trees need in order to grow e.g. sunlight, water and minerals, sunlight being the single most critical factor for *T. grandis*.

As mentioned previously two settings according to the initial stand size are examined, but also three sub-settings according to site quality. Site qualities are determined similarly as in Pérez and Kanninen's study (2005a) by reducing DBH and height growth functions to either 80% or 60% for medium and low quality sites, respectively. Without growth reduction the model represents the highest site quality with 100% growth potential.

3 RESULTS

First are presented the results without applying thinnings to the model, second are the results for the model with thinnings, third are the results for sensitivity analysis applied to the model with thinnings, fourth are the results of testing the heartwood proportion multiplier with the model, and fifth the results when applying suggested Pérez and Kanninen’s (2005) management regimes with the model and parameters used in our study. Medium site quality should ideally illustrate the growth of an average plantation in Costa Rica. Later on we refer to optimal management regime with thinnings as the ‘control’.

3.1 Optimal rotation without thinnings

Table 4 shows the optimal rotation length without any thinnings and the diameter at breast height at the time of the final cut. Rotation length varies from 10 to 18 years depending on the used rate of interest and stand site quality. Correspondingly diameter at breast height varies from 23.5 cm to 32.5 cm. As comparative statics suggests the higher rate of interest decreases the rotation length. The shortest rotation is obtained with 816 initial stand density at high quality site and 12.5% interest rate.

Table 4. Optimal rotation length T and DBH at the time of final felling without thinnings.

	Initial stand - Site quality											
	1111-High		1111-Medium		1111-Low		816-High		816-Medium		816-Low	
Rate of interest	T	DBH	T	DBH	T	DBH	T	DBH	T	DBH	T	DBH
5%	15	31.2	16	28.7	18	25.4	14	32.5	15	29.7	18	26.5
7.5%	13	29.0	14	27.0	16	24.2	12	30.2	13	27.8	17	25.8
10%	12	27.9	13	26.0	15	23.5	11	29.0	12	26.8	16	25.2
12.5%	11	26.7	12	25.1	15	23.5	10	27.7	12	26.8	15	24.4

As shown in Figure 3 mean annual increment (MAI) is higher when the site quality is better. In addition MAI is higher when the initial planting density is 1111 instead of 816. Annual average yield (MAI) with 5% rate of interest for planting density of 1111 at high, medium and low site quality is 21.4, 15.9 and 10.4 m^3 ha^{-1} a^{-1}, respectively. Similarly for planting density of 816 MAIs are 21.9, 16.2 and 9.9 m^3 ha^{-1} a^{-1}, respectively. The result suggests that without thinnings 816 planting density is superior in volume production compared to planting density of 1111 at high and medium quality sites.

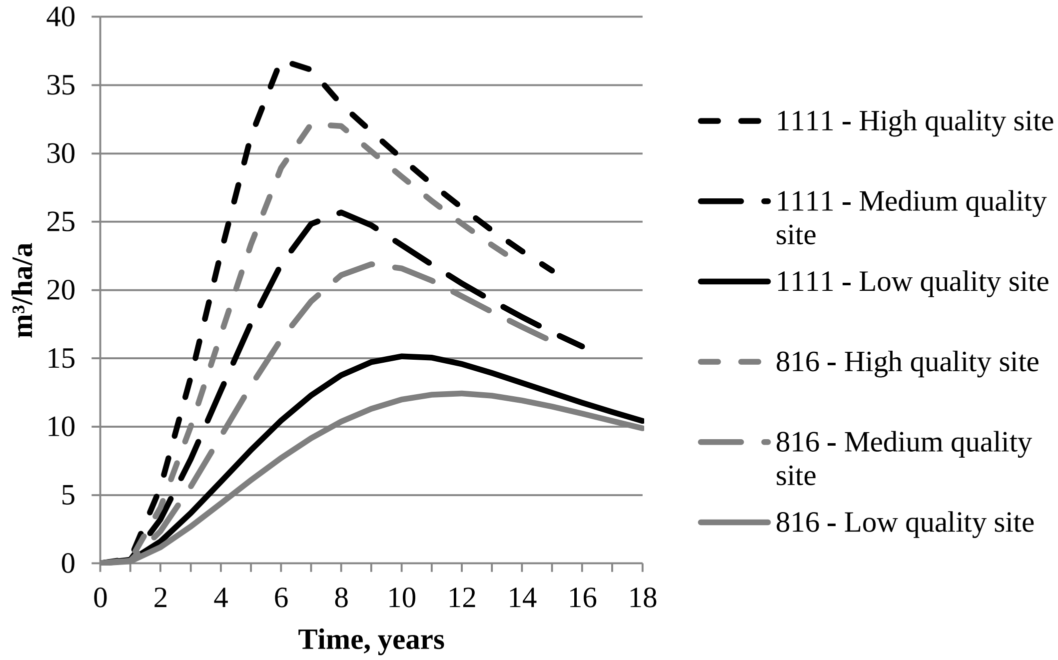

Figure 3. Mean annual increment under optimal rotation without thinnings, rate of interest 5%.

3.2 Optimal rotation with thinnings

The maximum rotation length with thinnings varies from 14 to 20 years depending on the site quality and rate of interest used (Table 5). With the initial state of 816 trees optimal rotation lengths are shorter than with the initial state of 1111 trees.

The rate of interest has a slight effect on the number of the thinnings. The site quality has more importance in the number of thinnings as it is unprofitable to do thinnings at low quality sites, because of the minor benefits from the treatment. The optimal number of thinnings is identical for both initial densities in almost all cases. Only in one occasion there is a smaller number of thinnings on initial state of 816 trees than on initial state of 1111 trees. With the rate of interest of 7.5% three thinnings are optimal whereas four thinnings are optimal for 1111 initial state. It is apparent that when the rate of interest increases, rotation length decreases and subsequently the number of thinnings decreases.

Table 5. Optimal rotation length and optimal number of thinnings.

	Initial stand - Site quality											
	1111-High		1111-Medium		1111-Low		816-High		816-Medium		816-Low	
Rate of interest	i	T	i	T	i	T	i	T	i	T	i	T
5%	4	16	2	17	1	20	4	16	2	17	1	20
7.5%	4	15	2	17	1	19	3	15	2	16	1	19
10%	3	14	2	16	1	18	3	14	2	15	1	18
12.5%	3	14	2	15	1	17	3	13	2	15	1	18

i = number of optimal thinnings, T = stand rotation length in years

The basal area when the thinning is carried out varies from 24.35 to 25.88 $m^2\ ha^{-1}$ at high quality sites for the initial state of 1111 trees (Figure 4a-d). As shown in Table 6 and Table 7 thinning intensities vary so that the first and the last thinnings on 1111 tree plantation are heavier, and on the 816 plantation the first thinning is lighter and the last two thinnings are heavier. In addition with 816 initial stand density the first thinning is one year later than with 1111 initial stand density. At medium quality site with 1111 initial trees the first thinning is postponed to seventh year and the plantation reaches stand basal area of 28.08 $m^2\ ha^{-1}$ after which a very heavy thinning is carried out.

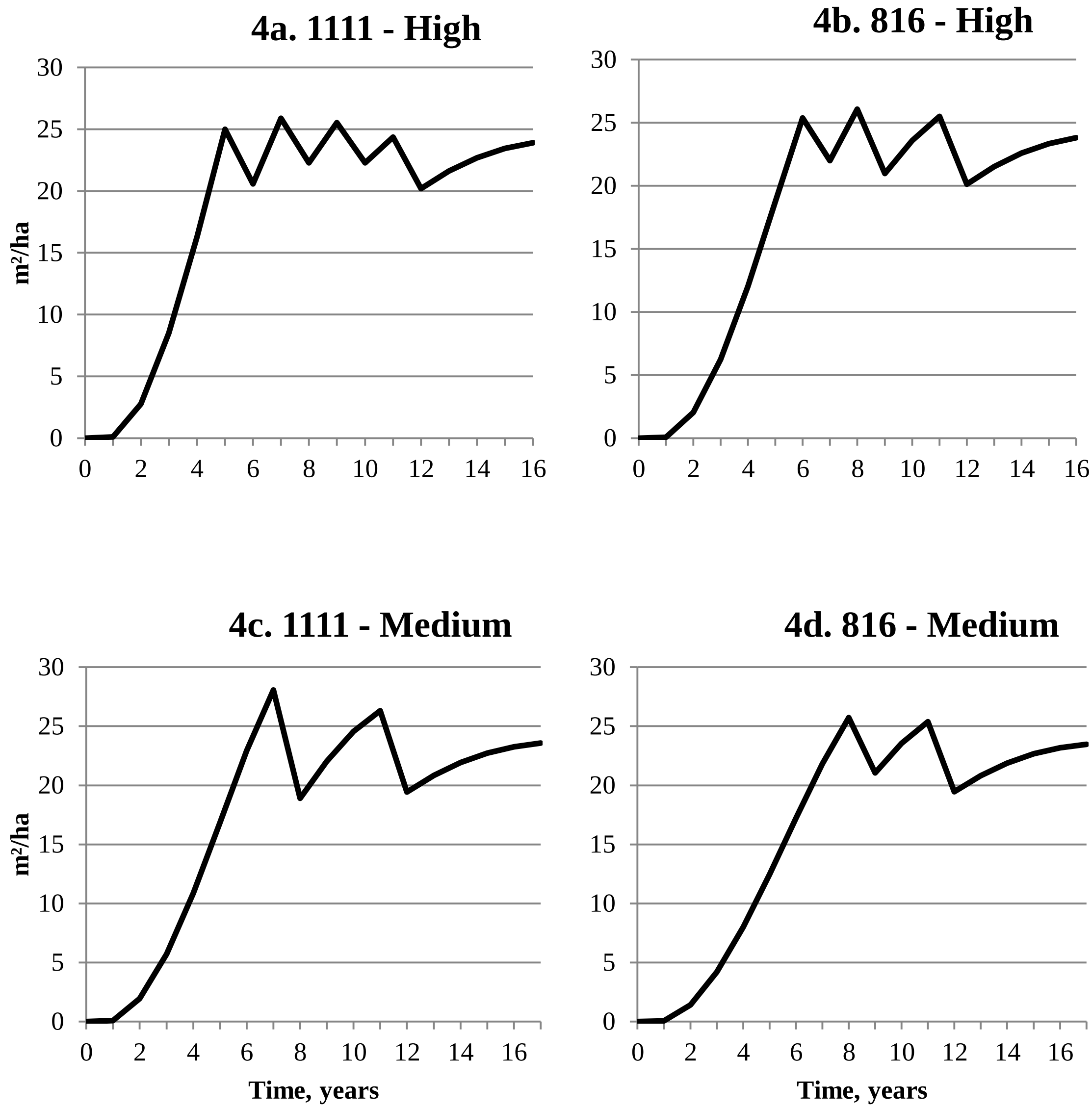

Figure 4a-d. Stand basal area, rate of interest 5%

Table 6 shows the timings of the thinnings, their intensities, produced merchantable volume, DBH and the roadside price after thinnings costs, i.e. the stumpage price, for a stand with a planting density of 1111 trees. The intensities of thinnings range from 18% to 36%. The average thinning intensity is 29%. The highest resulted DBH in the final cut is 39.8 cm and the lowest 25.8 cm. With 5% rate of interest the average tree height at the time of the final cut for high, medium and low site quality are 27.8, 22.8 and 18.1 meters, respectively. The average annual total mortality rate with 5% interest rate is 3.54%, 3.41% and 3.12% at high, medium and low quality site, respectively. When the stand basal area reached over 25 $m^2\ ha^{-1}$ the stand mortality increased over 5%.

Table 6. Thinning and final cut information. Initial stand density of 1111 trees.

	1111-High					1111-Medium					1111-Low				
Interest rate	*t*	Int. %	Vol. m^3	DBH cm	Price USD m^{-3}	*t*	Int. %	Vol. m^3	DBH cm	Price USD m^{-3}	*t*	Int. %	Vol. m^3	DBH cm	Price USD m^{-3}
5%	5	34	28.8	17.5	34.5	7	36	39.5	19.1	43.9	11	35	38.9	20.2	51.5
	7	23	34.4	23.2	73.1	11	27	44.9	26.0	96.9	20	100	136.6	27.6	111.3
	9	19	33.8	27.9	113.8	17	100	186.1	33.3	167.6					
	11	21	40.9	31.9	153.4										
	16	100	230.3	39.8	239.0										
7.5%	5	33	28.0	17.5	34.5	7	31	34.5	19.1	43.9	11	35	39.9	20.2	51.5
	7	24	36.0	23.2	73.0	10	30	45.1	24.4	83.0	19	100	132.8	27.1	106.1
	9	20	36.1	27.8	113.4	16	100	185.7	32.3	157.2					
	11	18	35.7	31.9	153.1										
	15	100	223.5	38.5	223.9										
10%	5	32	26.9	17.5	34.5	7	31	34.2	19.1	43.9	11	36	40.6	20.2	51.5
	7	31	47.0	23.1	72.9	10	33	49.6	24.4	83.0	18	100	128.1	26.4	100.5
	10	25	50.2	30.0	134.0	16	100	181.0	32.4	157.9					
	14	100	221.7	37.0	207.8										
12.5%	5	32	27.1	17.5	34.5	7	32	34.8	19.1	43.9	11	36	41.0	20.2	51.5
	7	25	38.6	23.2	72.9	10	31	47.1	24.4	83.1	17	100	122.5	25.8	94.5
	9	25	45.9	27.8	113.0	15	100	174.5	31.3	147.0					
	13	100	221.8	35.4	190.6										

Letter '*t*' indicates age in years. 'Int.' is the intensity, i.e. percentage of trees harvested. The volume 'Vol. m^3', is extracted merchantable volume. Prices are stumpage prices (over bark).

With initial state of 816 trees the characteristics in the management regime change in comparison to regime with initial planting density of 1111 trees. Thinnings are usually less intensive as one can observe from Table 7. In general the accumulated total yield is lower in 816 sites, but in return the stand average diameter at breast height is higher resulting in higher prices. The intensities of thinnings vary from 17% to 38%. The average thinning intensity is 25%, four percentage points lower than with initial density of 1111 trees. The highest attained diameter at breast height in the final cut is 40.1 cm and the lowest 26.9 cm. The average annual total mortality with 5% interest rate is 3.41%, 3.13% and 2.70% at high, medium and low quality site, respectively.

Table 7. Thinning and final cut information. Initial stand density of 816 trees.

	816-High					816-Medium					816-Low				
Interest rate	*t*	Int. %	Vol. m^3	DBH cm	Price USD m^{-3}	*t*	Int. %	Vol. m^3	DBH cm	Price USD m^{-3}	*t*	Int. %	Vol. m^3	DBH cm	Price USD m^{-3}
5%	6	26	31.6	20.7	55.1	8	24	29.6	21.4	59.7	13	27	32.3	22.8	69.8
	8	25	43.2	25.9	95.9	11	25	40.3	26.5	101.0	20	100	129.2	28.1	115.8
	11	23	48.2	32.3	156.9	17	100	184.7	33.8	173.0					
	16	100	228.9	40.1	242.2										
7.5%	6	26	31.6	20.7	55.1	8	25	30.3	21.4	59.7	13	29	34.8	22.8	69.8
	8	21	35.9	25.9	95.9	11	25	38.9	26.5	101.1	19	100	123.5	27.5	110.5
	10	25	47.2	30.2	136.5	16	100	178.9	32.8	162.9					
	15	100	228.3	38.8	227.6										
10%	6	26	31.4	20.7	55.1	8	26	31.4	21.4	59.7	13	31	36.9	22.8	69.8
	8	22	38.2	25.9	95.9	11	23	35.7	26.5	101.2	18	100	116.7	26.9	104.7
	10	22	40.9	30.3	136.6	15	100	172.4	31.8	152.0					
	14	100	221.0	37.4	211.6										
12.5%	6	26	31.4	20.7	55.1	8	27	32.3	21.4	59.7	13	38	45.5	22.8	69.8
	8	24	40.9	25.9	95.9	11	26	40.9	26.5	101.3	18	100	122.5	27.0	105.2
	10	17	31.1	30.3	136.8	15	100	165.3	31.9	152.8					
	13	100	214.0	35.8	194.5										

Letter '*t*' indicates age in years. 'Int.' is the intensity, i.e. percentage of trees harvested. The volume 'Vol. m^3', is extracted merchantable volume. Prices are stumpage prices (over bark).

Figure 5a-d and Figure 6a-d illustrate the changes in the number of the trees per hectare. The first thinning is heaviest across the board. At the end of the rotation the optimal number of trees for final cut is around 200 trees at the high quality site and 300 trees at the medium quality site. The figures illustrate how mortality is affecting the number of trees throughout the rotation.

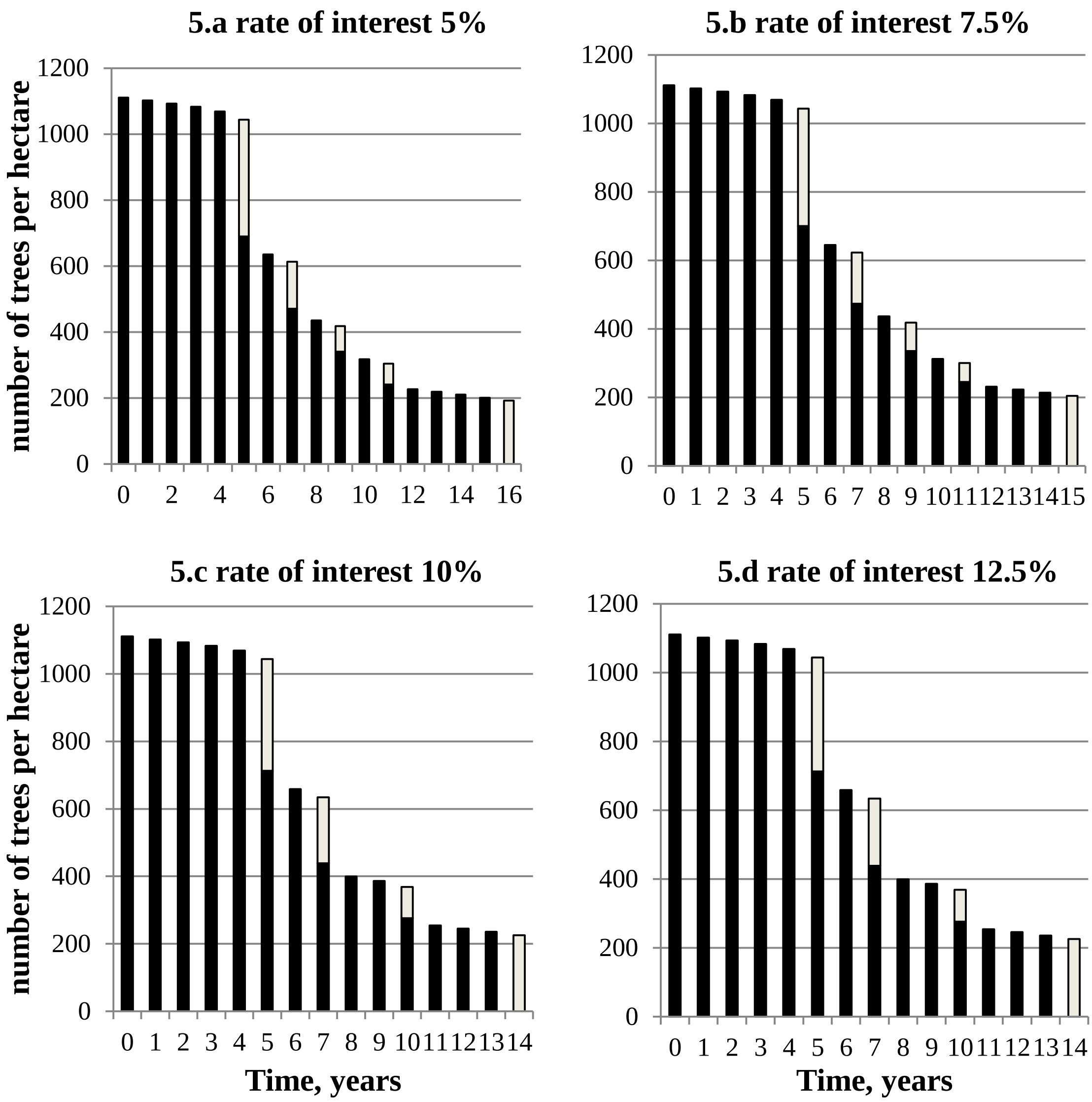

Figure 5a-d. Number of trees in the stand within optimal thinnings and final cut with initial stand density of 1111 trees and high quality sites.

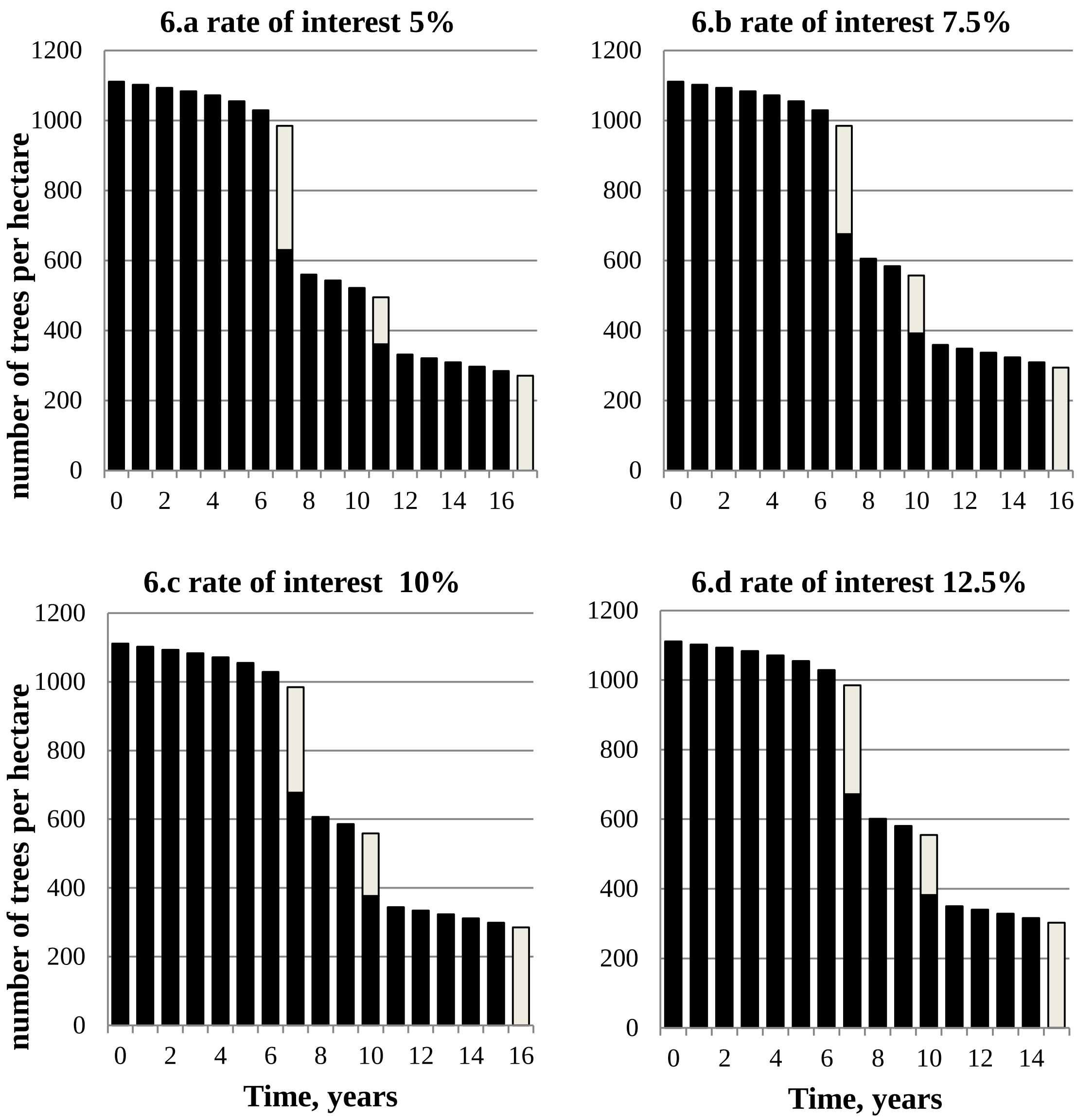

Figure 6a-d. Number of trees in the stand within optimal thinnings and final cut with initial stand density of 1111 trees and medium quality site.

As illustrated in Figure 7 the mean annual increment is different with the optimized thinnings in comparison to optimal solution without thinnings. MAI does not attain as high values as seen earlier in Figure 3 when there are no thinnings involved. This is because of the longer optimal rotations. Economically optimal solutions with thinnings return higher bare land values than optimal solutions when thinnings are not introduced. The bare land values of *T. grandis* plantations with optimal rotation length and without thinnings are shown in Table 8. The results show that the initial planting density of the stand has a notable effect on bare land values as stands with 816 initial states attain higher bare land values. This reflects the avoided costs from early thinning and avoided early competition between trees.

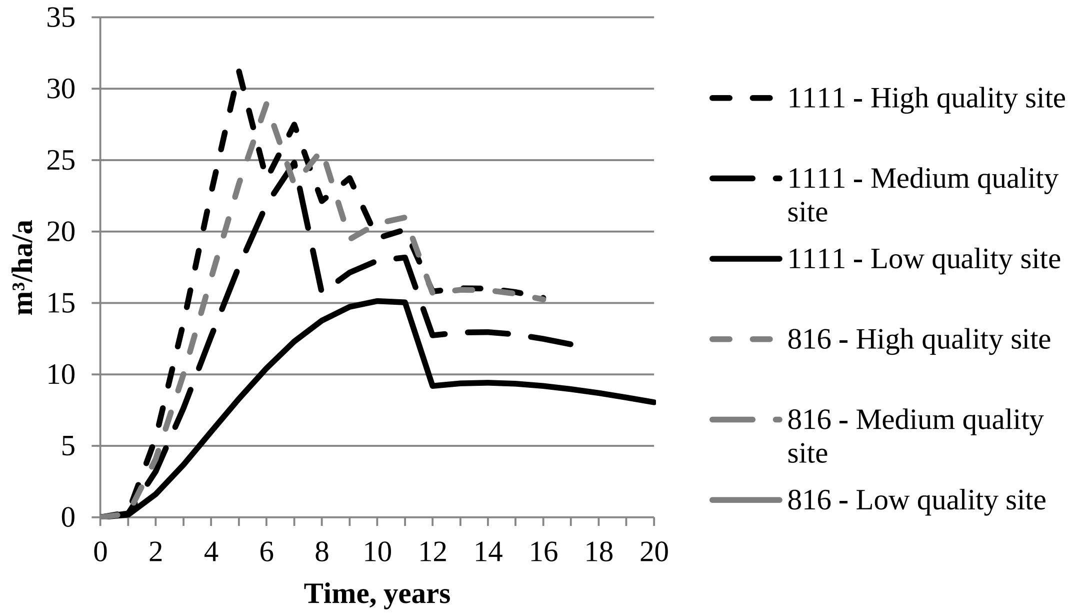

Figure 7. Mean annual increment with optimal thinning, 1111 initial planting density, 5% and 7.5% rate of interests.

Table 8. Bare land values without thinnings, USD ha^{-1}.

Rate of interest	Initial stand - Site quality					
	1111-High	1111-Medium	1111-Low	816-High	816-Medium	816-Low
5%	29 744	14 322	2 558	35 575	17 477	3 347
7.5%	14 708	6 188	-311	18 301	8 060	117
10%	7 936	2 547	-1 535	10 436	3 796	-1 267
12.5%	4 299	621	-2 139	6 165	1 521	-1 963

The bare land values of *T. grandis* plantations with thinnings are shown in Table 9. Including thinnings improves bare land values at high quality sites at 5% interest rate 21 557 USD ha^{-1} and 16 322 USD ha^{-1} with planting density of 1111 and 816, respectively. The corresponding increases at 12.5% interest rate are 5 354 USD ha^{-1} and 3 643 USD ha^{-1} with planting density of 1111 and 816, respectively. Similarly, at medium quality sites the bare land values are 7 365 to 1 673 USD ha^{-1} and 4 613 to 829 USD ha^{-1} higher, and at low quality sites the bare land values are 1 010 to 220 USD ha^{-1} and 282 to 52 USD ha^{-1} higher.

Table 9. Bare land values with thinnings, USD ha^{-1}.

Rate of interest	Initial stand - Site quality					
	1111-High	1111-Medium	1111-Low	816-High	816-Medium	816-Low
5%	51 301	21 687	3 568	51 897	22 090	3 629
7.5%	27 106	10 305	232	27 472	10 506	248
10%	15 841	5 079	-1 185	16 121	5 197	-1 185
12.5%	9 653	2 294	-1 919	9 808	2 350	-1 911

3.3 Sensitivity analysis

Sensitivity analysis is carried out for the price function used in the model. Price adjustments of +20% and -20% are optimized with thinnings. As this kind of adjustment scales the optimal solution similarly as adjusting costs, it was decided to carry out sensitivity analysis only for the price function.

Table 10 shows that bare land values logically increase across the board. Still the inferior sites show negative bare land values with interest rates of 10% and 12.5%. Increasing price increases the optimal initial planting density to 1111 at low quality sites and at medium quality site with rate of interest of 12.5%.

Table 10. Bare land value with +20% to price, USD ha^{-1}.

	Initial stand - Site quality					
Rate of interest	1111-High	1111-Medium	1111-Low	816-High	816-Medium	816-Low
5%	64 276	28 384	6 176	64 743	28 645	6 083
7.5%	34 477	14 025	1 663	34 724	14 139	1 570
10%	20 542	7 463	-336	20 760	7 470	-405
12.5%	12 900	3 872	-1 365	12 980	3 857	-1 408

Table 11 shows that minor changes happen to optimal rotation length when price increases. Overall the rotation length shortens. Optimal number of thinnings changes only in one occasion for both planting densities. On 1111 planting density with medium site quality it is optimal to have three instead of two harvests with interest rate of 5%. On planting density of 816 the rotation length shortened at high quality site with 5% interest rate resulting into one less thinning. With 12.5% rate of interest at high quality site the rotation length shortens from 14 to 13 years. Most significantly at the lowest site quality the rotation time is one year shorter independent of initial stand density or rate of interest. Additionally with 1111 planting density, at medium site quality and rate of interest ranging from 7.5% to 12.5% the rotation length is one year shorter with the price increase than in the control results.

Table 11. The optimal number of thinnings and rotation length with +20% to price.

	Initial stand - Site quality											
	1111-High		1111-Medium		1111-Low		816-High		816-Medium		816-Low	
Rate of interest	i	T	i	T	i	T	i	T	i	T	i	T
5%	4	16	3	17	1	19	3	15	2	17	1	19
7.5%	4	15	2	16	1	18	3	15	2	16	1	18
10%	3	14	2	15	1	17	3	14	2	15	1	17
12.5%	3	13	2	14	1	16	3	13	2	14	1	17

i = number of optimal thinnings, T = stand rotation length in years

With price increase optimal management regime does not change significantly (Table 12). The intensities of thinnings remain roughly the same. Only notable differences are caused when there are changes in the number of thinnings. With 1111 planting density only medium site quality with 5% rate of interest have such change. Table 13 shows that with lower price low quality sites are no longer economically viable except with 5% rate of interest. The reduction in wood price favors the 816 initial density over 1111 density.

Table 12. Thinning and final cut information with +20% to price. Initial stand density of 1111 trees.

	1111-High					1111-Medium					1111-Low				
Interest rate	*t*	Int. %	Vol. m³	DBH cm	Price USD m^{-3}	*t*	Int. %	Vol. m³	DBH cm	Price USD m^{-3}	*t*	Int. %	Vol. m³	DBH cm	Price USD m^{-3}
5%	5	34	28.7	17.5	47.5	6	29	19.0	16.8	43.7	11	33	37.1	20.2	66.8
	7	23	34.9	23.2	91.8	9	25	34.6	23.1	90.6	19	100	135.8	27.6	129.8
	9	19	33.8	27.9	139.4	12	20	33.3	27.7	137.5					
	11	21	40.9	31.9	186.2	17	100	180.9	33.6	206.7					
	16	100	230.1	39.8	288.0										
7.5%	5	33	27.9	17.5	47.5	7	32	34.7	19.1	58.1	11	34	37.7	20.2	66.8
	7	24	36.4	23.2	91.6	10	30	45.4	24.4	103.3	18	100	131.5	27.1	123.3
	9	20	36.2	27.8	138.9	16	100	185.1	32.3	191.0					
	11	18	35.7	31.9	185.9										
	15	100	223.2	38.5	270.2										
10%	5	32	26.9	17.5	47.5	7	32	35.0	19.1	58.1	11	34	38	20.2	66.8
	7	31	47.4	23.1	91.5	10	28	43.0	24.4	103.4	17	100	126.3	25.7	116.3
	10	25	50.3	30.0	163.3	15	100	179.0	31.2	178.1					
	14	100	221.2	37.0	251.0										
12.5%	5	32	27.1	17.5	47.5	7	33	35.8	19.1	58.1	10	34	32.4	20.1	58.8
	7	26	39.0	23.2	91.6	10	26	38.9	24.4	103.6	16	100	126.0	25.1	110.6
	9	26	45.9	27.8	138.5	15	100	172.2	30.1	164.4					
	13	100	221.3	35.4	230.6										

Letter '*t*' indicates age in years. 'Int.' is the intensity, i.e. percentage of trees harvested. The volume 'Vol. m³', is extracted merchantable volume. Prices are stumpage prices (over bark).

Table 13. Bare land values with -20% from price, USD ha^{-1}.

	Initial stand - Site quality					
Rate of interest	1111-High	1111-Medium	1111-Low	816-High	816-Medium	816-Low
5%	38 394	15 049	1 023	39 075	15 535	1 199
7.5%	19 766	6 610	-1 117	20 220	6 881	-1 011
10%	11 140	2 772	-2 019	11 482	2 961	-1 941
12.5%	6 417	726	-2 456	6 672	852	-2 389

Table 14 shows that with reduced prices the optimal rotation length becomes longer in some settings as the comparative statics generally suggests in forest economics. In most cases the reduction of prices does not have significant impact. Low quality sites have longer rotation under lower prices. Overall the increase in rotation length is more pronounced lower the site quality is. The number of thinnings is affected only at high quality sites where with initial density of 1111 trees and 7.5% rate of interest the optimal number of thinnings drops from four to three. Similarly in 816 initial density and 5% rate of interest the optimal number of thinnings decrease from four to three.

Table 14. The optimal number of thinnings and rotation length with -20% from price.

	Initial stand - Site quality											
	1111-High		1111-Medium		1111-Low		816-High		816-Medium		816-Low	
Rate of interest	i	T	i	T	i	T	i	T	i	T	i	T
5%	4	16	2	18	1	20	3	16	2	17	1	21
7.5%	3	15	2	17	1	19	3	15	2	16	1	20
10%	3	14	2	16	1	19	3	14	2	16	1	19
12.5%	3	14	2	15	1	18	3	14	2	15	1	19

i = number of optimal thinnings, T = stand rotation length in years

More significant changes in the optimal management regime follow from reducing the prices than from increasing the prices (Table 15). With initial stand density of 1111 trees, 5% rate of interest and high quality site first thinning become significantly earlier and heavier than in control. With interest rate of 7.5% as the number of thinnings decrease, the intensity of remaining thinnings increase. In general thinning intensities decrease. The highest change in DBH at the time of final harvest compared to control is +1.6 cm at high quality site with interest rate of 12.5%. Likewise the clear cut volume had only minor differences compared to control.

Table 15. Thinning and final cut information with -20% to price. Initial stand density of 1111 trees.

	1111-High					1111-Medium					1111-Low				
Interest rate	*t*	Int. %	Vol. m^3	DBH cm	Price USD m^{-3}	*t*	Int. %	Vol. m^3	DBH cm	Price USD m^{-3}	*t*	Int. %	Vol. m^3	DBH cm	Price USD m^{-3}
5%	2	39	0.0	5.7	0.0	7	36	39.0	19.1	29.7	11	34	37.8	20.2	36.2
	7	24	37.1	23.7	57.8	11	30	49.7	26.0	74.1	20	100	137.6	27.6	85.9
	9	18	32.9	28.3	91.5	18	100	187.1	34.2	140.1					
	11	20	40.4	32.3	124.2										
	16	100	229.1	40.2	193.8										
7.5%	5	33	27.7	17.5	21.5	7	35	38.9	19.1	29.7	11	34	38.6	20.2	36.2
	7	29	44.1	23.2	54.3	11	30	50.0	26.0	74.0	19	100	134.2	27.0	81.6
	10	27	55.5	30.0	104.8	17	100	181.7	33.3	132.4					
	15	100	229.6	38.4	177.7										
10%	5	32	27.0	17.5	21.5	7	36	39.2	19.1	29.7	11	38	42.3	20.2	36.2
	7	30	46.3	23.1	54.2	11	30	48.9	26.0	74.1	19	100	130.0	27.1	82.2
	10	25	50.1	30.0	104.7	16	100	175.3	32.3	124.1					
	14	100	222.3	37.0	164.6										
12.5%	5	31	26.2	17.5	21.5	7	31	34.2	19.1	29.7	11	38	43.0	20.2	36.2
	7	31	48.2	23.1	54.1	10	31	46.6	24.4	62.6	18	100	125.0	26.5	77.5
	10	28	55.4	29.9	104.4	15	100	175.9	31.3	115.1					
	14	100	215.8	37.0	164.9										

Letter '*t*' indicates age in years. 'Int.' is the intensity, i.e. percentage of trees harvested. The volume 'Vol. m^3', is extracted merchantable volume. Prices are stumpage prices (over bark).

3.4 Heartwood proportion testing

The effects of adding heartwood proportion to have direct multiplying effect on price is tested with an initial stand density of 1111 trees. A scaling factor is used for multiplying the heartwood proportion modified price, so that price is similar to the price used in the control when the stand average DBH is 40 cm. The testing intends to add accuracy to the pricing as the heartwood content is clearly the most valued and desired part of *T. grandis* timber and the original price data might be misrepresenting younger trees' values by pricing them too high.

Table 16 shows the number of thinnings, stand rotation length and bare land values for the optimal management regimes with heartwood proportion multiplying the price function. Bare land values are overall lower compared to control, particularly at low quality sites. At medium or low quality sites, as the number of thinnings decreases by one the rotation length decreases with two years. With all the other optimizations in our study, rotation length decreased only with one year when number of thinnings decreased by one. This suggests that the rotation length is more sensitive to number of thinnings when heartwood proportion is considered. When comparing to control values one less thinning is carried out at high quality site when interest rate is 7.5%. At low quality sites with interest rates of 5% and 7.5% one thinning more is carried out than in control due to longer optimal rotation length. Rotation periods are two years longer at high quality site, two to three years longer at medium quality site and four to five years longer at low quality sites than in control.

Table 16. The optimal number of thinnings, rotation length and bare land value (USD ha^{-1}) with heartwood proportion testing.

	Initial stand - Site quality						Initial stand - Site quality		
	1111-High		1111-Med.		1111-Low		1111-High	1111-Med.	1111-Low
Rate of interest	i	T	i	T	i	T	BLV	BLV	BLV
5%	4	18	3	20	2	24	50 164	17 339	36
7.5%	3	17	2	18	2	23	25 198	7 249	-1 857
10%	3	16	2	17	1	21	13 907	2 822	-2 537
12.5%	3	15	2	17	1	21	7 842	519	-2 826

i = number of optimal thinnings, T = stand rotation length in years

Table 17 shows the optimal results with heartwood proportion multiplying the price function. Prices are notably lower when the average DBH is low, and naturally prices are especially low in the early phase of the plantation. First thinnings at high and medium quality sites are made early in the rotation at the second, third or fourth year of the rotation. In addition the first thinning is heavy at both high and medium quality sites ranging from 45% to 56% thinning intensity and being non-commercial (no merchantable timber). The following thinnings are notably lighter commercial thinnings. The diameter at breast height is higher across the board when compared to the control optimization. The highest DBH of 43.3 cm resulted in a heartwood proportion of 54% in the final cut and the lowest DBH of 27.8 cm resulted in heartwood proportion of 37%. The first thinnings are earlier at high quality sites for all rates of interests, but the following thinnings are postponed. Similar phenomenon results at medium quality site, except with the 5% rate of interest where the whole regime is significantly different than in control as a result from one additional thinning and three years longer rotation. With 5% rate of interest the average tree height at the time of the final cut for high, medium and low site quality are 29.1, 24.1 and 19.0 meters, respectively.

Table 17. Thinning and final cut information under heartwood proportion testing.

	1111-High					1111-Medium					1111-Low				
Interest rate	*t*	Int. %	Vol. m³	DBH cm	Price USD m^{-3}	*t*	Int. %	Vol. m³	DBH cm	Price USD m^{-3}	*t*	Int. %	Vol. m³	DBH cm	Price USD m^{-3}
5%	2	54	0.0	5.7	0.0	3	49	0.0	8.2	0.0	5	36	0.0	11.0	0.0
	8	18	29.8	26.6	66.9	11	20	31.9	27.0	71.0	16	26	35.5	25.5	56.4
	10	19	35.7	31.0	116.6	14	19	32.4	31.0	116.5	24	100	122.8	30.2	107.0
	13	18	38.8	36.5	192.0	20	100	175.4	36.8	197.5					
	18	100	221.4	43.3	302.0										
7.5%	2	56	0.0	5.7	0.0	3	47	0.0	8.2	0.0	6	34	1.4	13.0	0.0
	9	25	47.0	28.9	92.3	11	29	48.3	26.9	70.3	16	31	42.4	25.4	55.7
	12	22	46.0	34.8	166.9	18	100	184.4	35.1	172.3	23	100	116.1	29.7	101.3
	17	100	219.9	42.1	282.4										
10%	3	50	0.0	10.0	0.0	4	46	0.0	11.4	0.0	13	33	44.1	22.0	26.0
	8	26	43.8	26.5	65.8	11	29	49.1	26.8	69.7	21	100	131.2	27.8	79.8
	11	26	53.2	32.8	140.0	17	100	180.0	34.1	158.3					
	16	100	220.1	40.8	259.5										
12.5%	3	49	0.0	10.0	0.0	4	45	0.0	11.4	0.0	13	37	49.2	22.0	26.0
	8	27	47.1	26.4	65.5	11	33	55.6	26.8	69.2	21	100	126.1	27.9	80.5
	11	24	48.6	32.8	139.4	17	100	174.6	34.2	158.4					
	15	100	213.5	39.4	236.7										

Letter '*t*' indicates age in years. 'Int.' is the intensity, i.e. percentage of trees harvested. The volume 'Vol. m³', is extracted merchantable volume. Prices are stumpage prices (over bark).

3.5 Simulation of previous management regimes

In order to compare the results found in the optimization, management regime parameters created by Pérez and Kanninen (2005a) are implemented into the optimization model used in our study. Prices and costs are different in their study, and therefore some bias is created to the comparison because of those. The aim of their research was either to maximize the stand volume or diameter at breast height. This is accomplished in their study by carrying out a thinning every time the competition factor (CF, same as used in the model of this thesis) reduces the DBH growth or volume growth by 20% and 50%, respectively. For clarification, as their paper states, the management regimes are scenarios instead of intending to generate economically optimal management regimes.

For the comparison purposes it was decided to use only scenarios with a total rotation length of 20 years and to exclude scenarios with 30-year rotations, because most of the results found in our study are below 20 years or barely over. In order to simulate the scenarios rotation length, intensity and timing of the thinnings were set according to the study by Pérez and Kanninen (2005a). Intensity and timing of the thinnings vary according to the site quality and maximizing objective as mentioned above.

Table 18 shows bare land values calculated with preset parameters set to model used in the optimization, instead of using optimizable variables for thinning or choosing the highest bare land value with different rotation lengths. The results show severe reduction in bare land values across the board. By using longer rotation time and the set thinning parameters, the low quality sites are no longer economically feasible investments with the rate of interests studied in this thesis. Severe decrease in bare land values at low quality sites is mainly because of excessive number of thinnings and hence excessive costs. With the same management scenarios medium quality sites are no longer economically feasible as the rate of interest increases over 10%. Furthermore, with 12.5% rate of interest neither of the preset management regimes is any longer feasible for any site quality.

Comparing positive results in Table 18 to the optimized results seen previously in Table 9 we find that with a higher site quality and a higher rate of interest decrease in bare land value is proportionally greater. In addition the aim to maximize DBH is more favorable of the preset management regimes when the site quality is high, but at the medium or low site quality the aim to maximize volume has higher bare land value from these two options. Observing the results with aim to maximize the volume, the management regime is economically more justified at medium quality site as the proportional decrease is lower than on a high site quality. With the aim to maximize DBH, the results suggest similar decrease for high and medium site quality, with 5% rate of interest. When supposedly maximizing the DBH with interest rate of 7.5%, the difference in decrease of the bare land value is already 7% between high and medium site quality in favor of high site quality. Oppositely with the aim to maximize volume the 7.5% rate of interest favors the high site quality over medium site quality.

As a comparison to optimized regimes, when the aim is to maximize DBH the losses in value range from 32 265 to 9 821 USD ha^{-1} at high quality sites depending on the rate of interest. Similarly at medium and low quality sites the losses in value range from 13 706 to 4 087 USD ha^{-1} and from 4 053 to 1093 USD ha^{-1}, respectively. As a comparison to optimized regimes, when the aim is to maximize volume the losses in value range from 33 996 to 9 984 USD ha^{-1} at high quality sites depending on the rate of interest. Similarly at medium and low quality sites the losses in value range from 11 753 to 3 787 USD ha^{-1} and from 3 950 to 1 041 USD ha^{-1}, respectively.

Table 18. Bare land values with preset management regimes by Pérez and Kanninen (2005a) with aim to maximize DBH or volume, USD ha^{-1}, and percentage loss when compared to optimal results.

	Initial stand - Site quality			Initial stand - Site quality		
	1111-High	1111-Med.	1111-Low	1111-High	1111-Med.	1111-Low
Interest rate	BLV DBH/ loss	BLV DBH/ loss	BLV DBH/ loss	BLV Volume/ loss	BLV max Volume/ loss	BLV Volume/ loss
5%	19 036/ 63%	7 981/ 63%	-485	17 305/ 66%	9 934/ 54%	-382
7.5%	7 435/ 73%	2 031/ 80%	-2 090	6 651/ 75%	2994/ 71%	-2015
10%	2 370/ 85%	-534	-2 734	1 999/ 87%	-9	-2 673
12.5%	-168	-1 793	-3 012	-332	-1 493	-2 960

Management regimes suggested by Pérez and Kanninen (2005a) produce much larger trees than the optimal management regimes suggested in our study (see Table 6 and Table 19). This is mainly due to longer rotation used in the preset management regimes. Nevertheless, bare land values are notably lower than in the optimized regimes, because of the slower value growth in the last years of the rotation. This is even more pronounced with higher rates of interest.

The first thinning is carried out earlier in almost every scenario when compared to optimal management regime, except at high quality site when the objective is to maximize volume (Figure 8a-f). The number of thinnings remains the same between optimal management and when objective is to maximize DBH, although the rotation time is four years shorter and thinnings notably lighter under the optimal management regime. At medium quality sites the differences between management scenarios when maximizing DBH or volume are minor. The only notable differences when compared to optimal management scenario are the early first thinning, one additional thinning and three years longer rotation time. The stand basal area is notably higher at the time of the final felling under optimal management regime when compared to preset regimes.

Table 19. Thinning and final cut information under preset management regimes suggested by Pérez and Kanninen (2005a).

	Initial stand – Site quality														
	1111-High					1111-Medium					1111-Low				
Objective	*t*	Int. %	Vol. m³	DBH cm	Price USD m⁻³	*t*	Int. %	Vol. m³	DBH cm	Price USD m⁻³	*t*	Int. %	Vol. m³	DBH cm	Price USD m⁻³
Maximize DBH	4	45	8.7	13.9	17.5	5	45	10.1	14.3	18.8	7	40	11.0	14.8	21.1
	8	45	80.8	26.2	98.5	10	40	58.1	25.2	90.1	13	40	41.2	22.9	71.3
	12	33	59.9	34.6	182.1	15	33	49.1	32.4	158.3	20	100	99.5	28.6	120.4
	16	25	41.8	41.1	253.3	20	100	128.2	37.3	211.2					
	20	100	152.0	45.8	306.2										
Maximize volume	6	50	75.4	20.3	52.0	5	40	9.0	14.3	18.8	9	40	30.2	17.9	36.9
	10	40	74.0	29.4	128.0	10	40	61.7	25.1	88.9	14	33	35.0	23.7	77.4
	15	40	76.1	38.3	222.6	15	25	38.7	32.1	155.6	20	100	102.5	28.3	117.8
	20	100	147.2	44.5	291.7	20	100	146.6	37.0	207.7					

Letter '*t*' indicates age in years. 'Int.' is the intensity, i.e. percentage of trees harvested. The volume 'Vol. m³', is extracted merchantable volume. Prices are stumpage prices (over bark).

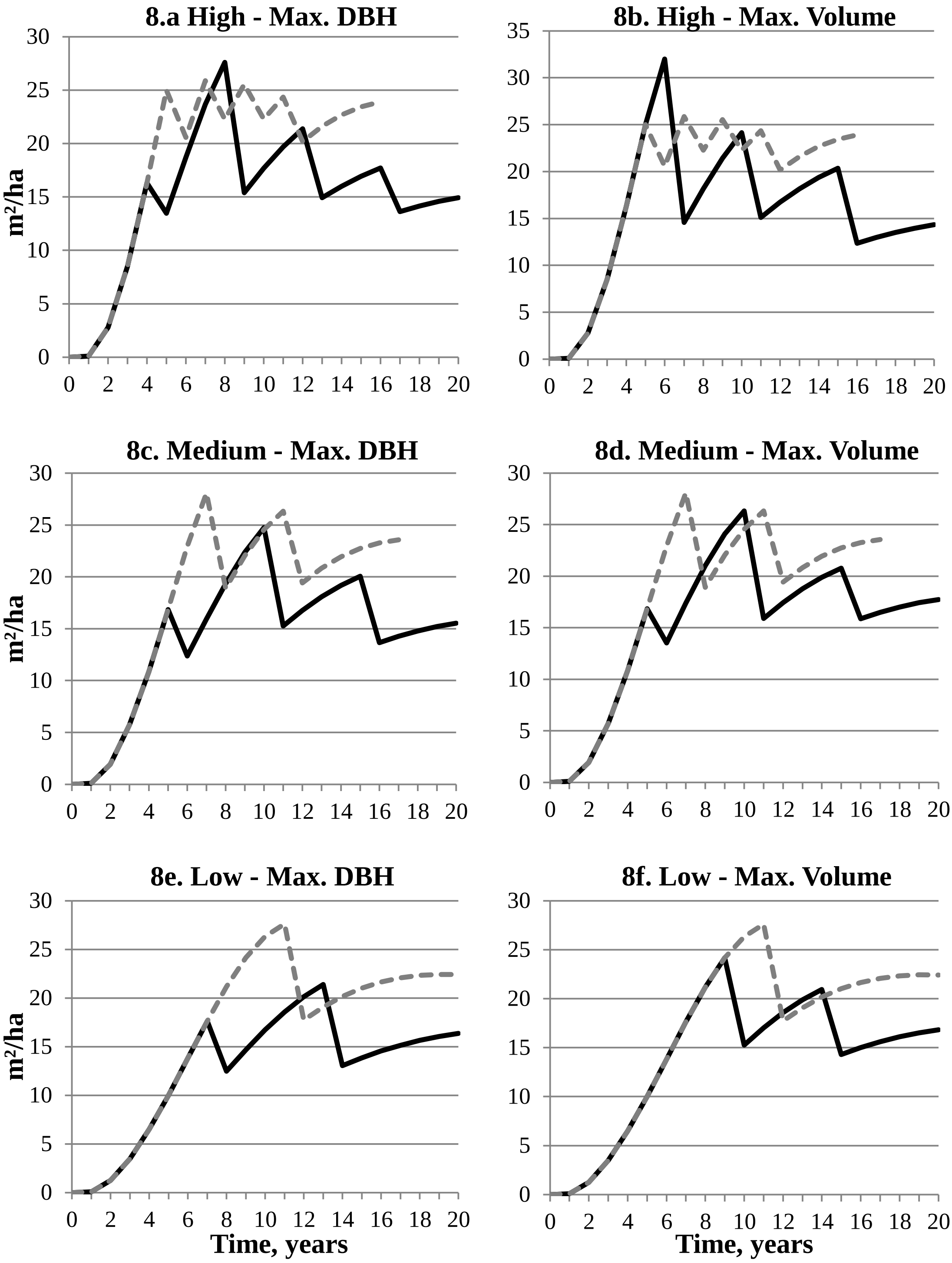

Figure 8a-f. Stand basal area with management regime suggested by Pérez and Kanninen (2005a) presented as the black line, the grey dashed line presents the stand basal area with optimal management, rate of interest 5%, initial stand density 1111 trees per ha.

4 DISCUSSION

In general the suggested *T. grandis* plantation rotation time in Latin America has commonly varied from 20 to 30 years (Table 20), the shortest suggested rotation for timber production being 17 years in Venezuela (Evans and Turnbull 2004). The longest studied rotations were 30 years (Pérez and Kanninen 2005b). Justification for the chosen rotation times is not discussed in length in any of the previous studies, even though in the light of our study it seems to be the single most important decision to be made in plantations. The importance of the rotation length is more stressing the higher is the preferred rate of interest. The shortest rotation time for Latin American *T. grandis* plantations found from the literature was 6 years, and such short rotation would indicate the end use purpose being manufacturing of poles for cattle ranches (Kollert and Cherubini 2012).

According to Isotupa and Tyynelä (2010) small-scale forest owners prefer *T. grandis* because of good price, global markets, profitability and because its risks are lower than with other crops. Even though our study may serve best in the interests of large industrial plantation owners, still the recommendations of this thesis may serve to benefit small and medium-scale plantation owners as well, as it offers theoretically and rationally sound choices that should not be neglected when creating forest management guidelines for forest owners. Especially large international investors are likely to require such forest management plan, which results into the highest bare land value with the preferred rate of interest. Many of the *T. grandis* plantations in Costa Rica are of small or medium size, so called smallholder plantations whose livelihoods are highly dependent on their land use choice. Industrial-scale *T. grandis* plantations that are over several thousands of hectares are rare, and currently such plantations exist mainly in Brazil. As the demand of *T. grandis* stays high and harvests of *T. grandis* from natural forests are declining, it is more probable that larger plantations are established with more intensive and sophisticated management.

Another significant trend is that farmers are changing from seedlings towards clone plantations. As shown in study by Isotupa and Tyynelä (2010) the attitudes of small-scale farmers in Costa Rica are positive towards using clones as the plantation material. Industrial plantation businesses are adopting fast new vegetative propagation technologies as they have the resources to access genetic materials more easily or introduce clone trials in their own laboratories (Coutinho 2013). Clones seem to have superior growth characteristics when compared to non-modified seedlings, but more comprehensive research on the benefits is still ongoing (Finkeldey 2013). Planting costs are higher with clones, but the initial stand may be less dense, which would indicate lower thinning costs in the future.

In our study two different initial stand options are analyzed, with either 1111 or 816 seedlings. The cost structure varied only on the behalf of planting costs ignoring other effects such as need for extra weeding in the early years at the plantation. According to the used optimization the 816 seedlings option resulted slightly higher bare land values. Optimization does not consider subsequent increase in growing of the tree crown, which would likely result from the available space for the trees to grow (Kanninen 2012). This could likely cause an increase in pruning costs.

The average diameter at breast height in the clear cut in our study may be argued to be lower than in practice. Only at the best site qualities the optimization reached a stand average DBH of over 40 cm. If the highest log prices are attained from notably larger trees (DBH >40 cm) then the price function should be calibrated accordingly. Interestingly the heartwood proportion test resulted in high DBH at the final cut and lower prices from thinnings, which could be a more accurate interpretation of price dynamics. According to the study by Pérez and Kanninen (2003b) the proportion of the heartwood as a function of DBH has its fastest growth below DBH of 30 cm. In addition stand density is shown to have some effect on the heartwood proportion. The higher the stand density is the lower the heartwood proportion is. This could suggest that the trees on the 816 initial planting density plantations have a higher heartwood proportion and therefore have a higher price.

Table 20. Rotation length suggested or studied in previous literature and in our study.

Study	Country/Region	Rotation min	Rotation max	Reasoning for rotation
Pérez 2005	Costa Rica	20	30	Maximum volume or DBH
Griess & Knoke 2011	Panama	-	25	Profitability, NPV & BLV
Cubbage et al. 2010	Venezuela	-	21	Profitability, NPV & BLV
Puolakka 2003	Costa Rica	20	28	Profitability, NPV
Isotupa & Tyynelä 2010	Costa Rica	25	29	Profitability, NPV
Bermejo et al. 2004	Costa Rica	-	25	Preset silvicultural regime for growth model
Evans & Turnbull 2004 (p. 285[1])	Central America	10	22	Maximum volume production
Kollert & Cherubini 2012	Costa Rica	6	30	Current practice
De Vriend 1998	Costa Rica	20	30	Profitability, NPV & BLV
Study in hand[2] 2013	Costa Rica	16	20	Economic optimum, BLV
Study in hand[2] with heartwood testing 2013	Costa Rica	18	24	Economic optimum, BLV

[1] Citation to Keogh, R.M. 1980. *T. grandis* volume growth and thinning practice in the Caribbean, Central America, Venezuela and Colombia. In *Wood production in the neotropics via plantations* (ed. J.L. Whitmore), pp. 58-71. Proceedings of the IUFRO/MAB/Forest Service Symposium, Rio Pedras, Puerto Rico, September 1980. [2] With interest rate of 5% and depending on the site quality.

The payment for ecosystem services program (PPSA) was introduced with the new forest law in 1996 (Forestry Law No. 7575) in Costa Rica. It comprises three types of land uses that are entitled to payments for ecosystem services (Lindhjem et al. 2010):

1. Forest protection – commitment to 5 year duration 210 USD ha^{-1}
2. Sustainable forest management – commitment to 15 year duration 327 USD ha^{-1}
3. Reforestation activities – commitment to 15 to 20 year duration 537 USD ha^{-1}

In the light of our study, most of the optimal management regimes for *T. grandis* plantations could qualify for funding from the above program at least on behalf of the rotation length as the required commitment for reforestation activities range from

15 to 20 years. In addition other criteria are considered when determining the eligibility of the project, e.g. carbon sequestration potential, hydrological importance, proximity to existing protected areas and size of the plantation. For private owners the maximum reforestation area under this program is 300 hectares and minimum of 1 hectare. Payments are received in installments so that 50% is received in the first year, 20% in the second year, 15% in the third year, 10% in the fourth year and 5% in the fifth year (Pagiola 2008). The agreement to continue the land use for 15 years is transferred among the land title in case the land is sold. During the commitment period the maximum harvesting intensity is 40% and trees under a certain DBH are not allowed to be harvested. The highest thinning intensities according to our control results are 38%. The optimization yields highest thinning intensities at low quality sites where it is economically optimal to carry out only one thinning during the rotation. At higher quality sites several lighter thinnings are optimal. With the heartwood proportion testing the optimal first thinning at high and medium quality site ranges from 45% to 56% at the age of 2 to 4 years. These thinning intensities would be too high to be eligible within the legislation. If no initial density is set in the legislation then a sparse planting density, such as the 816 initial planting density, could lower the intensities of the first thinnings and thereby make the management legitimate. Thinning intensities suggested in other literature are usually heavier than 40% (see e.g. Puolakka 2003, Pérez and Kanninen 2005a).

A question arises if the payment is justified for such economic activity that is in principle profitable. Therefore it is important that the gained positive externalities are clearly and, when possible, monetarily indicated. Funding of the program by the National Forestry Financing Fund (FONAFIFO) is based on the national fuel tax revenues. Payments are targeted at carbon sequestration through the PPSA program. In addition carbon sequestration in forests create revenue through international carbon crediting mechanism; the clean development mechanism (CDM). Three fourth of applications have been rejected to PPSA program mainly because of the program's insufficient funding (Lindhjem et al. 2010). Payment for ecosystem services would likely have a notable impact on the optimal management if it would be bound to tCO_2e in the stand instead of being fixed per hectare. Models for carbon sequestration of *T. grandis* plantations in Panama already exist (see e.g. Kraenzel et al. 2003, Derwisch et al. 2009). Apparently the profitability for applying another kind of land use than forest planting is so high that the subsidy for reforestation activities has become a necessity.

4.1 Sensitivity analysis and heartwood proportion test on the price function

The results show that the rotation length decreases when price increases and vice versa. In addition, the number of thinnings is prone to decrease when the rotation length decreases. Site quality has the most apparent effect on the number of thinnings. In the sensitivity analysis price is set to increase or decrease evenly throughout the whole price function. No major changes in optimal plantation regime are noticed when increasing prices. The reduction of prices does cause in some settings an earlier timing of the first thinning, making the first thinning non-commercial. Non-commercial very early first thinning is even more apparent with heartwood proportion testing.

The effect of heartwood proportion change on price function was studied ad hoc. Due to lack of research on this specific issue these results are preliminary. In contrast it must be noted that results with heartwood proportion testing resemble the management regimes that are commonly applied in *T. grandis* plantations in Latin America, because of longer rotation time and earlier non-commercial thinning. Even though management regimes have similarities with previous studies, such as the heavy first thinning, it has to be duly noted that the rate of interest has a pronounced effect on the bare land value, rotation length and characteristics of the thinnings. In comparison to control results, the rotation length in heartwood proportion test is two years longer at high quality sites, two to three years longer at medium quality sites and four to five years longer at low quality sites. In the optimization results for high quality sites the thinning patterns changed to favor single heavy thinning early on and then few lighter thinnings later in the rotation. A heavy thinning early on would ignite fast growth as individual trees had more resources for their disposal. As mentioned before in a study by Bamber (1976), the heavy thinning may lead into rapid growth of the tree crown, dampening the growth of heartwood proportion. In a more recent study Peréz and Kanninen (2003b) suggested that the heartwood proportion is more related to the growth of DBH and therefore a low density plantation may have better heartwood proportion growth. A study by Arce (2001) showed higher heartwood proportions for stands with a density of 830 trees per hectare in comparison to stands with 1111 trees per hectare density in 10-year-old *T. grandis* plantations.

As illustrated in the Figure 1 the price of *T. grandis* in the global market is increasing. The sensitivity analysis shows that the rotation length is sensitive to the wood price changes. However, it is unclear from the aggregate import price figures available which size of logs with which kind of characteristics are actually increasing in price in the market. The *T. grandis* prices which are publicly available or the ones provided for our study do not indicate the relationship with heartwood as the prices are simply either log prices recorded from the final cut or from late thinning. The prices do not reveal what has been the DBH of the tree before felling or the heartwood proportion.

4.2 Comparison to previous studies

Few studies have examined the profitability of *T. grandis* plantations in Latin America. Six studies were found comparable or worth noting separately. Out of the six studies, one was carried out in Panama, one in Venezuela and the rest in Costa Rica. As seen in Table 9, our study suggests a bare land value of 21 687 USD ha^{-1} for a medium quality site with 5% rate of interest with an initial density of 1111 trees. None of the previous studies have tried to optimize rotation length or thinnings in Costa Rica, although simulations with different scenarios have been tested in some studies. The previous studies calculating economic profitability did not note that increasing the rate of interest has been proven in forest economics to normally reduce the rotation length (see e.g. Hyytiäinen and Tahvonen 2002, Alvarez and Koskela 2003).

The only paper found studying the economic optimization problem of *T. grandis* plantations was made in India (Jayaraman and Rugmini 2008). No sufficient comparison can be made to our study, because in their study the rotation length was not a freely optimized variable and because the target country was India. However, Jayaraman and Rugmini (2008) did find a similar result presenting how the rate of interest significantly reduces the rotation length when maximizing net present value.

The earliest profitability study found was by de Vriend (1998, p. 50-51). He calculated annual income with 8% interest rate to illustrate the changes in profitability when applying rotation length of 20, 25 or 30 years. He concluded that with the applied interest rate the most profitable rotation length was 20 years, except at low quality site a 25 year rotation resulted in the highest annual income. De Vriend (1998, p. 48) calculated also bare land values for the Pacific and the Atlantic region with 8% interest rate and 20 years rotation. In the Pacific region the BLV for low, medium and high quality sites were 13 923, 22 713 and 30 803 USD ha^{-1}, respectively. In the Atlantic region the BLV for low, medium and high quality sites were 18 817, 29 156 and 40 174 USD ha^{-1}, respectively.

The second earliest of the previous profitability studies found was by Puolakka (2003). In his study two *T. grandis* plantation companies were studied and net present values of 7 187 USD ha^{-1} and 19 895 USD ha^{-1} were obtained for the companies with 5% rate of interest. Default rotation time for both companies was 24 years, using four heavy thinnings during the rotation. The aimed final cut was allegedly supplying 221.7 m^3 ha^{-1} with a DBH of 46.6 cm, and 230.6 m^3 ha^{-1} with a DBH of 47.9 cm for the other company, respectively to above mentioned bare land values. Puolakka (2003) performed several profitability simulations by differing thinnings and their intensities. According to Puolakka's (2003) results, different thinning programs did not have notable effect on the profitability. Puolakka (2003) argued against the common belief that very intensive thinnings are more profitable than frequently repeated less intensive thinnings. The results from our study show similarly that thinnings may be relatively light in comparison to other studies on thinnings (see e.g. Pérez 2005).

In Pérez's dissertation (Pérez 2005) a net present value of 27 453 USD ha^{-1} was calculated with 5% rate of interest. The above net present value was obtained at a medium quality site, when the management objective was to maximize diameter at breast height with a 20 years rotation. The study simulated management regimes by changing thinnings and either aiming at maximizing the total merchantable volume of the stand or the diameter at the end of the rotation. Thinning decisions were based on the competitiveness factor (CF) and Pérez (2005) concluded that for the optimal growth basal area should be kept at 20 to 25 m^2 ha^{-1} in order to avoid excessive competition. In our study the options for management regimes are wider because the thinnings are freely optimized. In our study the basal area prior to thinning range from 19 to 28 $m^2\ ha^{-1}$. The highest basal area prior to the thinning is achieved at a medium site quality with 1111 trees (Figure 4). As the tree growth is slower when compared to high quality site the optimal strategy is to wait for more valuable logs for the first thinning and then have an intensive thinning, which reduces the basal area close or even below to 20 $m^2\ ha^{-1}$. Logically the thinning is not as intensive on plantations with 816 initial planting density. When comparing two different initial stand densities in our study one of the clearest indications is that the first thinning is approximately 10% more intensive across the board for the 1111 initial stand density.

In a study by Isotupa and Tyynelä (2010) net present value of 12 330 USD ha^{-1} was estimated for a *T. grandis* plantation with 5% rate of interest, with a site index referring to maximum basal area of 18 $m^2\ ha^{-1}$, initial stand density of 816 trees and rotation length of 25 years (Isotupa and Tyynelä 2010). Net present value of 12 814 USD ha^{-1} was estimated for a *T. grandis* plantation with 5% rate of interest, with a site index referring to maximum basal area of 18 $m^2\ ha^{-1}$, with initial stand density of 1111 trees and rotation length of 26 years. Net present value of 14 308 USD ha^{-1} was estimated for a *T. grandis* plantation with 5% rate of interest, with a site index referring to maximum basal area of 20 $m^2\ ha^{-1}$, initial stand density of 1111 trees and rotation length of 28 years. Net present value of 14 284 USD ha^{-1} was estimated for a *T. grandis* plantation with 5% rate of interest, with a site index referred to maximum basal area of 20 $m^2\ ha^{-1}$, initial stand density of 816 trees and rotation length of 29 years. The rotation times seem excessively high in comparison to results in our study. Also the above mentioned 18 and 20 $m^2\ ha^{-1}$ stand basal areas referred to the site qualities where the latter is a better site with higher growth. This also contradicts with the suggestion of our study that the rotation time should be shorter at higher site qualities. Additionally, Isotupa and Tyynelä (2010) carried out a survey asking the small-scale *T. grandis* plantations owners about their profitability expectations. The survey resulted in expected net present values ranging from 7 890 to 39 448 USD ha^{-1}, while the median of the answers was 13 807 USD ha^{-1}.

In a study by Griess and Knoke (2011) the net present value and bare land value were calculated on Panamanian *T. grandis* plantations. According to the study the "pessimistic" net present value for *T. grandis* plantation was 2 982 USD ha^{-1} and the "optimistic" 23 551 USD ha^{-1} with a rotation length of 25 years, initial stand density of 714 trees and 5% rate of interest. The study suggests a volume of 413 m^3 ha^{-1} at the end of the rotation with a stand average DBH of 37 cm. Interestingly, the stand had an average DBH of 29.8 cm and volume of 233 m^3 ha^{-1} at the age of 17 years. These values are somewhat the same as results in our study. Two thinnings were scheduled for years 8 and 10 with intensities of 41% and 14%, respectively. In the light of our study the mentioned thinning schedule is not sensible. The study does not indicate specific values for bare land values, but instead illustrates the development of bare land value over the entire rotation with a graph. At 6% rate of interest the optimal rotation is approximately 22 years and the bare land value is approximately 10 000 USD ha^{-1}. Griess and Knoke (2011) conclude that the profitability of *T. grandis* is below the profitability of other native species. However, a study by Piotto et al. (2004) suggests that *T. grandis* has better combined growth and survival rates than the native species in Costa Rica. Apparently as an introduced exotic species *T. grandis* lacks competition and threats it might have in its land of origin in Southeast Asia.

Cubbage et al. (2010) reported bare land value of 9800 USD ha^{-1} with 8% rate of interest and total volume of 312 m^3 ha^{-1}. In their study the rotation age was 21 years and target country was Venezuela. The results in our study with rate of interest of 7.5% range from 6 188 to 18 301 USD ha^{-1} at medium to high quality sites respectively and by altering planting density.

In the study by Bermejo et al. (2004) growth equations and total volume projections were developed for *T. grandis* plantations in Northwestern Costa Rica. The final cut in the projections was carried out at the age of 25 for three different site qualities. The DBH at the time of the final cut was 43.9 cm, 36.1 cm and 31.5 cm, from the highest to the lowest site quality respectively. All of the regimes included five thinnings prior to final cut. Initial stand density was 1111 trees. When compared to the study in hand final cut diameters at breast height are not notably higher even though the plantation had at least five years longer rotation time in their study.

A study by Kanninen et al. (2004) focused on establishing guidelines for the appropriate intensity and timing of the first thinning of *T. grandis* plantations in Costa Rica. Kanninen et al. (2004) suggested that the first thinning should be very intensive

(40-60%) at the age of four years. The study was performed for a stand with initial number of 1600 trees. The study suggests that the later thinnings should be carried out when the basal area reaches values between 22 and 26 $m^2\ ha^{-1}$. The results of this thesis suggest that the first thinning is usually carried out at the age of 5 to 8 years at high and medium quality sites and is not as heavy as suggested by Kanninen et al. (2004). This result may be due to the lower initial density in our study as the trees have not yet started to compete as much as they would with a higher density. Also the heartwood proportion testing resulted in a slightly similar outcome of a heavy early thinning. In our study the basal area before thinning varies between 19 to 29 $m^2\ ha^{-1}$, which is a wider range than in Kanninen et al. (2004). The study by Kanninen et al. (2004) recommends four thinnings for plantations with 20 to 25 year rotation length. Morataya et al. (1999) also suggested a heavy early thinning, for the reason that *T. grandis* attains its best height growth in 6 to 8 years of age.

Simulating the model of our study with preset management regime, as suggested by Pérez and Kanninen (2005a), results in significantly lower bare land values than the optimal thinning and final cut regime in our study. Bare land values with preset management regime are considerably lower even than those bare land values resulting from the optimization without thinnings. This suggests that the single most important forest management decision dictating the bare land value is the rotation length and how the rate of interest affects that. Furthermore the optimal rotations without thinnings are the shortest when compared to any other management regime in this thesis. When the optimal rotation without thinnings is found, shortening the rotation length has a greater negative effect on the bare land value than lengthening the rotation.

4.3 Critique of the model

In order to achieve more accurate results we suggest a more thorough price, cost and growth data collection with higher sample sizes. Obviously the strength of optimizing a forest management regime is most apparent when more individual details about the site specific growth and owner's rate of interest preferences are determined. Admittedly the price function used is the weak point of our study. The price accuracy should be developed further with a more accurate use of a taper function and bucking, and taking into account heartwood proportion in the tree. The price data itself should be more accurate. An international pricing mechanism should be developed to make the *T. grandis* pricing publicly available and the price data should be validated (Keogh 2008). Using the stem model created by Pérez (2008) a more accurate taper function could be utilized in the model, which would help determining the optimal bucking of the trees.

Further ecological study on the size class distribution in *T. grandis* plantations would help to develop the optimization model more accurately. This way the type of thinning could be determined, i.e. whether the thinnings should be from above or below. As noted earlier in our study, thinnings carried out in *T. grandis* plantations in Costa Rica are usually thinnings from below (Piotto et al. 2004). Controversially to the above mentioned practice some economic studies done on other species have shown that in fact it is optimal to harvest from above when the interest rate is higher (Cao et al. 2006). The explanation for this is that it is economically more sensible to harvest trees that have already achieved their best value growth and ignite growth of smaller trees by removing large trees shading them. One study about size class distribution was found for Brazilian *T. grandis* plantations (Nogueira et al. 2006). No other diameter distribution models for *T. grandis* were found published during the writing of this thesis.

Another shortcoming of the ecological model is the absence of the interrelation between stand density and canopy growth, canopy growth and heartwood proportion growth, and subsequently heartwood proportion and the price of logs. Faster canopy growth may favor growth of sapwood instead of heartwood as the canopy then requires more water and minerals through the sapwood (Morataya et al. 1999). The value of the logs decreases with heartwood content. The above mentioned chain of interrelation would likely have an effect on the optimization. A further study on the effects of rapid growth of *T. grandis* should be carried out as well. It has been argued that fast growth of *T. grandis* causes growth of pith in the medulla of the tree, which reduces a commercially viable sawing pattern area of the logs.

Perhaps the most significant step forward in modeling *T. grandis* growth would be creating a physiological process-based growth model, such as the pipe model used in forest ecology (Mäkelä et al. 2000). Such a model would be more practical in a changing environment than a statistical growth model. Creating such model would be challenging in case of plantation *T. grandis*, as the genetics of the planted species is continuously improved (Monteuuis and Maître 2007).

Fixed thinning costs should be determined more accurately. It is logical that optimal removal of trees would likely to be annual or at least extremely frequent if no cost is introduced, for example, to the mobilizing and planning of a thinning. In addition it may be suggested that such fixed cost would dramatically change according to the size and ownership type of the plantation (Pérez 2005). The organizing costs of thinning decrease with increasing treated forest area due to economies of scale. It may be fair to assume that an individual small-holder would need to spend relatively more resources than a larger asset owner such as company or a financial institution, which is more likely to have tools and capacity for such activities at its exposal. On the other hand smallholders or communities may be located in a close proximity to the plantation and therefore be able to practice continuous light harvesting without having to bear extra costs.

5 CONCLUSIONS

The model of this thesis was formulated in order to optimize *T. grandis* plantation management regime from an economic perspective. The results show that the profitability of *T. grandis* plantations is highly sensitive to rotation time, site quality, interest rate and price dynamics. The accuracy of our study is heavily dependent on the ecological model, but as well on the price and cost data. Bare land values resulting from the optimization are in the same range as in previous profitability studies. Our study also suggests the bare land value is slightly higher with the initial density of 816 than with the 1111 initial density. In further studies it should be tested how setting initial stand density as a freely optimized variable changes the optimization results. In order to set initial stand density as a freely optimized variable and to attain sensible results the ecological dynamics of the model needs to be revised. Especially crown growth of the tree and competition with other species are probably affected by the initial stand density.

The answers to the *hypotheses* presented in the beginning of the thesis:

1. *The optimal rotation length in T. grandis plantations is different than what is commonly suggested for T. grandis plantation management in Costa Rica.* The optimal rotation length varies according to site quality and the used rate of interest. In addition the price of timber has an effect on rotation length. The higher the price the shorter is the rotation. When compared to previous studies our study suggests shorter rotation times than those that are commonly used in Costa Rica. In addition losses in bare land value when using excessively long rotations are substantial in the light of our study.
2. *The optimal number, timing, and intensity of thinnings vary due to multiple reasons.* The optimal number of thinnings varies significantly between different site qualities. Different interest rates and timber price slightly affect the number of thinnings. Significant changes in the optimal rotation may affect the optimal number of thinnings. Timing of thinnings is mostly affected by the rotation time and price of timber. If the price is reduced significantly a heavy non-commercial first thinning may become optimal. The optimal intensity of thinning is affected by intensities and timings of other thinnings or

rotation length, and by price changes. In addition the initial stand density affects the optimal harvesting.

3. *Changes in price will notably affect the end results.* Adjusting price does have direct effects across the board. Naturally bare land value rises as the price is higher and vice versa. Effects on a management regime are not as major as were expected. Rotation length varies to some extent, and the effects on the number of optimal thinnings are minor. Optimal management regime is more sensitive to price changes that affect certain log diameters more than others. The prices used in our study should be examined further in order to increase the overall accuracy.
4. *Heartwood content changes the plantation management regime.* According to the ad hoc test the overall effect of heartwood proportion growth does affect the optimal plantation management regime. Because of the simplicity of the test and lack of research on the dynamics of heartwood growth in relation to the stand density it has to be noted that this particular hypothesis needs significant additional study. Features related to *T. grandis* characteristics, which are not effectively covered in our study, are the factors that are likely to affect heartwood growth, such as canopy growth in relation to stand density. The heartwood proportion testing results in our study suggests that timing of the thinning and, more importantly, rotation length is affected. The first thinning is carried out earlier and in a heavier manner to boost future DBH growth. In addition the first thinning in the management regime determined in heartwood testing is non-commercial.
5. *Descriptive theory outcome; what does happen. What happens when T. grandis plantation regime is optimized?* The optimized *T. grandis* plantation regime gives higher economical profit to an investor or a forest owner than regimes reported in studies without optimization. The higher the interest rate the higher are the proportionate losses in bare land value from using preset management regime instead of optimized management regime. One may observe that the optimal management regime is different for different site qualities, and to investors with different rate of interest preferences. The optimized management regime is also significantly different from common practice in Costa Rica.

6. *Normative theory outcome; what should happen. What kind of policies or silviculture recommendations should follow from the optimization results?* This thesis suggests that a closer look should be taken into optimizing the *T. grandis* plantation management regime in order to maximize bare land value. The price function used in our study should be under scrutiny, and if it is found accurate then the results of this thesis may be used as rough guidelines for choosing a management regime of *T. grandis* plantations in Costa Rica. Undoubtedly more accuracy may be introduced to the applied model by improving the accuracy of the biological growth model of *T. grandis* and log pricing. Extending the current model with a diameter distribution model would help to determine the optimal type of the thinning. In addition, especially at the low quality sites, it is obvious that no *T. grandis* plantation investments should be introduced with interest rates that result in negative bare land values. Current policies used for subsidizing *T. grandis* plantations need more clarification on why subsidies are justified, i.e. what are the benefits from positive externalities. Furthermore, these benefits should be monetized, and introduced into the optimization model.

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APPENDICES

Appendix 1. Run file. AMPL with KNITRO.

```
### Miika Malmström (2013) ###

# Single tree model, run file #

# Growth model by Pérez (2005) and Kanninen (2000) #

reset;

model tiikki1111c4.mod.txt;

data tiikki1111c4.dat.txt;

option solver knitroampl;

option knitro_options "maxit=500 opttol=1.0e-8 outlev=0";# ms_enable=1
ms_maxsolves=5"; #par_numthreads=8";

for {timeloop in 25..10 by -1} {

let maxt2:=25;

let maxt:=timeloop;

let best_J:=-1e+6;

for {W in 1..maxt-1}{

  let t1:=W;

    for {W2 in W+1..maxt-1} {

    let t2:=W2;

      for {W3 in W2+1..maxt-1} {

      let t3:=W3;

        for {W4 in W3+1..maxt-1} {

         let t4:=W4;

            solve; #Thinning loops

           let FX:= ((if H[t1] > 1e-2 then (-350*exp(-r*t1)) else 0)+

        (if H[t2] > 1e-2 then (-350*exp(-r*t2)) else 0)+

        (if H[t3] > 1e-2 then (-350*exp(-r*t3)) else 0)+
```

```
(if H[t4] > 1e-2 then (-350*exp(-r*t4)) else 0)+
(if n[maxt] > 0 then (-350*exp(-r*maxt)) else 0))/(1-exp(-r*maxt));
        #Costs per hectare, silviculture costs and harvest mobilizing costs
    if J+FX > best_J
     then {
      let best_J:= J+FX;
      let best_maxt:= maxt;
      let best_t1:= t1;
      let best_t2:= t2;
      let best_t3:= t3;
      let best_t4:= t4;
      let {loop in 0..maxt} best_n[loop]:= n[loop];
      let best_H1:= H[t1];
      let best_H2:= H[t2];
      let best_H3:= H[t3];
      let best_H4:= H[t4];
      let best_p1:= p[t1];
      let best_p2:= p[t2];
      let best_p3:= p[t3];
      let best_p4:= p[t4];
      let {loop in 0..maxt} best_p[loop]:= p[loop];
      let best_D1:= D[t1];
      let best_D2:= D[t2];
      let best_D3:= D[t3];
      let best_D4:= D[t4];
      let {loop in 0..maxt} best_D[loop]:= D[loop];
      let best_mV1:= mV[t1];
```

```
let best_mV2:= mV[t2];
let best_mV3:= mV[t3];
let best_mV4:= mV[t4];
let best_X:= X;
let best_FX:= FX;
let {loop in 0..maxt} best_C[loop] := C[loop];
let {loop in 0..maxt} best_V[loop] := V[loop];
let {loop in 0..maxt} best_d[loop] := d[loop];
let {loop in 0..maxt} best_h[loop] := h[loop];
let {loop in 0..maxt} best_MA[loop] := MA[loop];
let {loop in 0..maxt} best_MB[loop] := MB[loop];
let {loop in 0..maxt} best_m[loop] := m[loop];
let {loop in 0..maxt} best_z[loop] := z[loop];
let {loop in 1..maxt} best_mV[loop]:= mV[loop];
let {loop in 0..maxt} best_BAs[loop]:= BAs[loop];
let {loop in 0..maxt} best_H[loop]:= if loop = t1 or loop = t2 or loop = t3 or loop = t4 then H[loop] else 0;        #Loop for determining the highest BLV result
}}}}}}
```

Appendix 2. Model file. AMPL with KNITRO.

```
### Miika Malmström (2013) ###

# Single tree model, model file #

# Growth model by Pérez (2005) and Kanninen (2000) #

param maxt; #Rotation length

set T :=0..maxt;

param maxt2; #for optimization runs

param best_J default 0; #"best_" parameters for obtaining results with highest BLV as shown in run file

param best_maxt;

param best_t1 default 0;

param best_t2 default 0;

param best_t3 default 0;

param best_t4 default 0;

param best_H1;

param best_H2;

param best_H3;

param best_H4;

param best_n {t in 0..maxt2};

param best_p1;

param best_p2;

param best_p3;

param best_p4;

param best_p {t in 0..maxt2};

param best_D1;

param best_D2;

param best_D3;
```

```
param best_D4;
param best_D {t in 0..maxt2};
param best_mV1;
param best_mV2;
param best_mV3;
param best_mV4;
param best_h {t in 0..maxt2};
param best_mV {t in 0..maxt2};
param best_d {t in 0..maxt2};
param best_MA {t in 0..maxt2};
param best_MB {t in 0..maxt2};
param best_m {t in 0..maxt2};
param best_z {t in 0..maxt2};
param best_BAs {t in 0..maxt2};
param best_H {t in 0..maxt2};
param best_X;
param best_C {t in 0..maxt2};
param best_V {t in 0..maxt2};
param pi = 4 * atan(1);     #Set the value of pi to parameter
param dmax;                 #DBH-parameter
param i;                    #DBH-parameter
param j;                    #DBH-parameter
param hmax;                 #Height-parameter
param l;                    #Height-parameter
param o;                    #Height-parameter
param n0;                   #Initial stand
param a;                    #Mortality in relation to age-parameter
```

```
param b;                #Mortality in relation to age-parameter
param c;                #Mortality in relation to basal area-parameter
param x;                #Mortality in relation to basal area-parameter
param e;                #Total volume-parameter
param f;                #Total volume-parameter
param Q;                #Total volume-parameter
param g;                #Competition factor-parameter
param k;                #Competition factor-parameter
param A;                #Merchantable volume-parameter
param B;                 #Merchantable volume-parameter
param Z;                #Merchantable volume-parameter
param L;                #Merchantable volume-parameter
param t1;               #Timing of the first thinning
param t2;               #Timing of the second thinning
param t3;                #Timing of the third thinning
param t4;                #Timing of the fourth thinning
param FX;                #Total discounted fixed costs from thinning, see run file
param best_FX;
param w {t in T} =
if t = 0 then 2228.86
else if t = 1 then 484.66
else if t = 2 then 375.5
else if t = 3 then 75
else if t = 4 then 75
else if t = 5 then 75
else if t = 6 then 175
else if t = 7 then 142.5
```

```
else if t = 8 then 142.5

else if t >= 9 then 105;        #Fixed silviculture costs

param r;                        #Interest rate

var H {t in T}>=0;              #Variable for harvests

var n {t in T}>=0;              #Variable for number of the trees, notice that n[0] is pre-
set

param X = sum {t in 0..maxt}-w[t]*exp(-r*t);  #Sum of fixed silviculture costs

var z {t in T};                 #Current annual increment

var D {t in T} >= 0;            #Modified diameter at breast height

var p {t in T} = if D[t] <= 13 then 0 else (-
0.0039328215354928*D[t]^3+0.5019075888935730*D[t]^2-
10.5130171951496000*D[t]+116.387894389976); #Price

var C {t in T} = if D[t] <= 13 then 0 else 106.026924186309*exp(-
0.0714299367542353*D[t]); #Harvesting costs

param d {t in T} = (dmax*(1-exp(i*t)^j));            #Diameter at breast height as a
function of age

var BAs {t in T} = ((pi*((D[t]/2)^2))*n[t])/10000;    #Stand basal area

param MA {t in T} = a*exp(b*t);                       #Mortality as a function of age

var MB {t in T} = c*exp(x*BAs[t]);                    #Mortality as a function of basal
area

param h {t in T} = (hmax*(1-exp(l*t)^o));             #Height as a function of age

var m {t in T} = 1-g*exp(k*BAs[t]);   #Diameter growth modification factor, i.e.
competition factor

var V {t in 0..maxt} = (e*(D[t]^f)*(h[t]^Q))*n[t];    #Total volume as a function of
time

var MV {t in 1..maxt} = (1-A*(L)^B*(D[t])^Z);      #Proportion of merchantable
volume

var mV {t in 1..maxt} = V[t]*MV[t];                   #Total merchantable volume

var J = (X+H[t1]*(((p[t1]-C[t1])*mV[t1])/n[t1])*exp(-r*t1)+H[t2]*(((p[t2]-
C[t2])*mV[t2])/n[t2])*exp(-r*t2)+H[t3]*(((p[t3]-C[t3])*mV[t3])/n[t3])*exp(-
r*t3)+H[t4]*(((p[t4]-C[t4])*mV[t4])/n[t4])*exp(-r*t4)+exp(-r*maxt)*((p[maxt]-
```

```
C[maxt])*mV[maxt]))/(1-exp(-r*maxt));                    #Faustmann, objective function with possibility for four thinnings

maximize objective:

    J;

subject to moddiameter {t in 0..maxt-1}:

  D[t+1] = D[t]+z[t]*m[t];                          #Modified diameter at breast height for next period

subject to CAI {t in 0..maxt-1}:

  z[t+1] = d[t+1]-d[t];                             #Current annual increment for next period

subject to trees {t in 0..maxt-1}:

  n[t+1] = n[t]-n[t]*MA[t]-n[t]*MB[t]-if t=t1 then H[t] else if t=t2 then H[t] else if t=t3 then H[t] else if t=t4 then H[t] else 0;    #Number of trees available for next period after mortality and harvest(s)

subject to initial_CAI:                             #Initial Current annual increment

  z[0] = 1;

subject to initial_diameter:                        #Initial modified diameter at breast height

  D[0]=d[0];

subject to initial_stand:                           #Initial number of trees

  n[0] = n0;

subject to mortalityconst {t in T}:                 #Nonnegativity constraint for mortality

  0 <= MB[t] <= 1;

subject to modifier {t in T}:                       #Nonnegativity constraint for competition factor

  0 <= m[t] <= 1;
```

Appendix 3. Data file. AMPL with KNITRO.

```
### Miika Malmström (2013) ###

# Single tree model, data file #

# Growth model by Pérez (2005) and Kanninen (2000) #

param n0:=1111;          #Trees planted in the beginning of rotation

param a:=0.0051;         #Mortality as a function of time parameters

param b:=0.015;          #Mortality as a function of time parameters

param c:=0.003;          #Mortality as a function of basal area parameters

param x:=0.11;           #Mortality as a function of basal area parameters

param e:=0.00007319;     #Total volume growth parameters

param f:=1.5588;         #Total volume growth parameters

param Q:=1.2103;         #Total volume growth parameters

param g:=0.003;          #Diameter growth modification factor

param k:=0.16;           #Diameter growth modification factor

param dmax:=60;          #Diameter growth parameters

param i:=-0.07;          #Diameter growth parameters

param j:=1.165;          #Diameter growth parameters

param hmax:=35;          #Height growth parameters

param l:=-0.09;          #Height growth parameters

param o:=1.1;            #Height growth parameters

param A:=0.7839;         #Merch. volume parameters

param B:=2.4149;         #Merch. volume parameters

param Z:=-2.4175;        #Merch. volume parameters

param L:=14;             #Upper stem merchantability limit

param r:=0.05;           #Rate of interest
```